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Thermal comfort in forested urban canyons of low building density. An assessment for the city of Mendoza, Argentina

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A B S T R A C T

This research has established the degree of comfort achieved in road channels of Mendoza Metropolitan Area (AMM), in Argentina. They present different widths (16 m, 20 m and 30 m) with low building density and they are forested with First (Platanus acerifolia) and Second (Morus alba and Fraxinus excelsior) Magnitude species. The methodology is based on the selection of cases, the experimental observation and the assessment of thermal comfort condition by applying the COMFA method. The energy budget evaluation shows that the road channels forested with Platanus acerifolia -whose green structure is characterized for continuous tunnel over street and sidewalk-, has the best behavior. Nevertheless taking into account the urban problems of the city under study, it is necessary to settle the comfort conditions with the possibility of nocturnal cooling. During the daytime the solar radiation control is a key to getting comfort conditions. During the nighttime, sky vision is needed for radiative cooling. In addition, the forest structure combined with the urban morphology increase soil roughness and reduces the convective cooling. Therefore it is necessary to encourage those combinations of forest structure and urban morphologies that benefit both processes in order to reduce the urban heat island.

1. Introduction

The assessment of energy balance is fundamental in order to understand how an urban design can modify the energy flows [1]. Moreover, the characterization of urban radiant fields and the thermal behavior resulting from their interactions with the urban morphology, the green structure and the local climate features is a basic tool to assess both energy consumption and the environmental pollution associated with urbanization. At the same time, data of the distribution of arid regions shows that many important cities are in dry lands. Also, approximately one third of the world population lives in extremely arid, arid or semi-arid regions and therefore cities located in these areas display a compact urban model characterized by narrow streets and buildings with interlaced small-sized backyards [2]. Created shades reduce the sun exposure in warmer seasons and, consequently, the heat accumulation on heavy material surfaces – surfaces with high thermal admittance.

The Mendoza Metropolitan Area (MMA) is located in central western Argentina, (32°40′ southern latitude, 68°51′ western longitude, 750 m above sea level) in a semi-arid continental climate with low percentages of atmospheric relative humidity and high heliophany. It corresponds to the aridity index of 0.20–0.50 (aridity index = precipitation/potential evapotranspiration) according to Maps of Desertification Hazard of Central Western Argentina [3] see Fig. 1. Although, MMA is located in a semi-arid region, it does not follow the aforementioned compact urban model. Their urban model is defined by its wide and tree-lined streets that form green tunnels. The checkered frame contains the buildings while the main strategy for minimizing the sun exposure is the vegetal frame. For this reason, the present study takes into account the impact on thermal comfort of the urban forestry along side the streets in MMA. Moreover, the study makes a contribution to a more general scholarly discussion. In recent years, the concept of sustainable development has stressed the fact that some urban forms significantly reduce energy consumption and pollution. For example, the "green urbanism" is broadly considered a better design for a more sustainable city [4]. In the last thirty years, we have seen an increasing scientific knowledge as well as a more general awareness about the beneficial effects of green areas and vegetal biomass [5–15].

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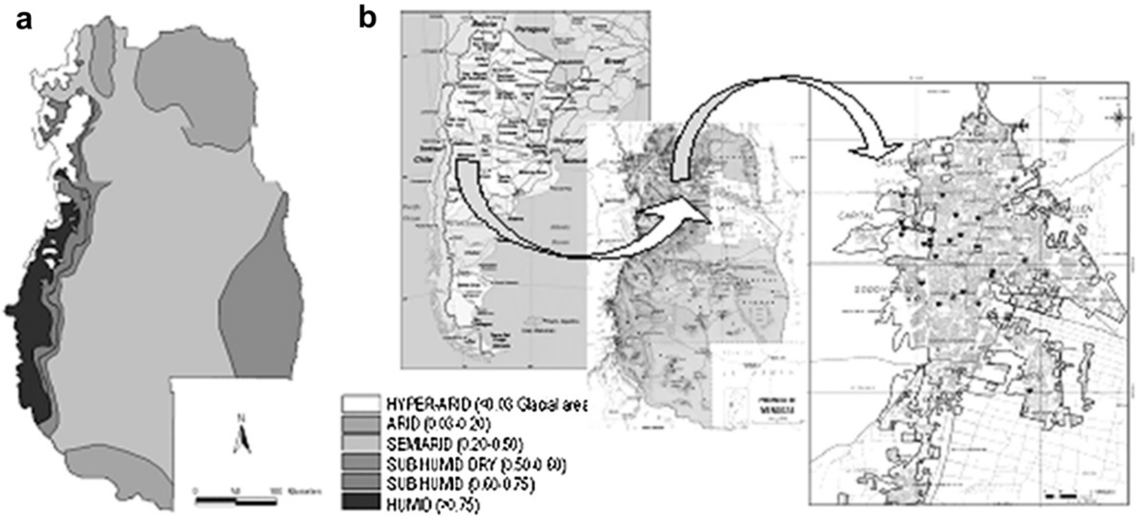

Fig. 1. a) Arid areas in Mendoza (aridity index = precipitation/potential evapotranspiration). b) Localization of the city studied in the province of Mendoza, Argentina.

Nevertheless, to properly estimate the real benefits of urban forestry we have to also consider how the urban morphology, cover and climate affect the growth and the health of tree species. This is so because urban morphology, cover and climate may cause both reduction in the beneficial effects and an increase in the cost of the urban forestry management. To start with, it is true that the value of an urban forest equals the net benefits that society obtains from it. [4]. Net benefits include an analysis of the relationships that the existing urban forest structure may develop as part of a more general ecological process. 'Structure' here refers to the way in which vegetation is arrayed in relation to other objects such as buildings [4,15]. In this sense, this work asses the thermal behavior of the typical green structures in the low building density of MMA.

2. Features of MMA

The city of Mendoza was founded in 1561 following the Spanish regular orthogonal grid that became the norm for all the Americas. The city morphology brought by the Spaniards had the ideal of not only an urban order but also a theological one [16]. See Fig. 2. In 1861 the colonial city was destroyed by a massive earthquake and the reconstructed city of Mendoza ended with wider streets of 20 m instead of the former of 16.71 m. The reason was that the French surveyor Julio Ballofet prepared the layouts using meters instead of the original yards of the Spanish legislation. Another major change was in 1872 when a system of ditches was implemented with a new design to provide with fresh water and to help with the drainage. Ditches were now built in parallel to the roads and they made possible the planting of public trees [16].

From that time on, urban forestation in MMA is the most important bioclimatic conditioning tool for open spaces during sun hours. In this sense, the city follows the model of any other oasis city. Nevertheless, the intense forestation with species of First and Second Magnitude forms a tunnel structure on road channels that decreases the sky view factor (SVF). At the same time, there is an increase in the land roughness. Negative impacts arise when these two effects are added to the low frequency and intensity of the winds. With predominance of bright days they all reduce the passive cooling by means of convection and radiation. Indeed, the urban heat island at night reaches 10 °C every season and the cooling needs increases the energy consumption by 20%. The figure evidences why we need to better assess the relationship between the forest structure and the morphological and climatic characteristics of MMA where the combination of both the urban and forestation shape have a detrimental effect in what otherwise was supposed to be mitigating –the urban heat island- [17].

On the other hand, some authors have also demonstrated that in order to achieve a better management of woody landscape in arid cities it is crucial to know the characteristics of surface energy balance and the response of different trees to the increased energy loads [18]. Inside this framework, the study of MMA is aimed at analyzing the energy and environmental behaviors of different frame-building-urban green settings.

3. Background

The classification of forest magnitude is based on the end height that a tree reaches 20 years after plantation. The First Magnitude is for species whose end height surpasses 15 m. The Second Magnitude goes from 8 to 15 m and the Third is for up to 8 m [19].

The green structure in urban canyons depends on the tree magnitude and the adaptation to the width and depth of the canyon. In MMA there are three main green structures: 1) a continuous tunnel over both the sidewalk and the street. It is forested with first magnitude trees like the Platanus acerifolia (see Fig. 3a); 2) a tunnel interrupted at the street level but a homogeneous screen over sidewalks. It is forested with second magnitude trees like Morus alba, which have an open crown (see Fig. 3b); and 3) an individual development of the forest without overlapping crown. It is forested with second magnitude tree like the Fraxinus excelsior, which has a compact crown (see Fig. 3c).

Considering the thermal behavior, the first green structure (Platanus acerifolia) offers the advantage of a shade and the reduction of sun gain over horizontal and vertical surroundings. It, however, may reduce the radiative and convective cooling possibilities. The second green structure (Morus alba) may increase the sun gain but may keep the shade over pedestrian spaces. It may also improve cooling during nights as a consequence of increasing the sky view factor and it may reduce the rugosity of site. The third green structure (Fraxinus excelsior), although it is the most unfavorable in terms of thermal behavior during summer daytimes, it may nevertheless offer the best condition for cooling. Taking into account these differences, more detailed studies of thermal behaviors of different trees in different urban conditions are needed [20]. We measure the thermal behavior of the green structures in the following cases:

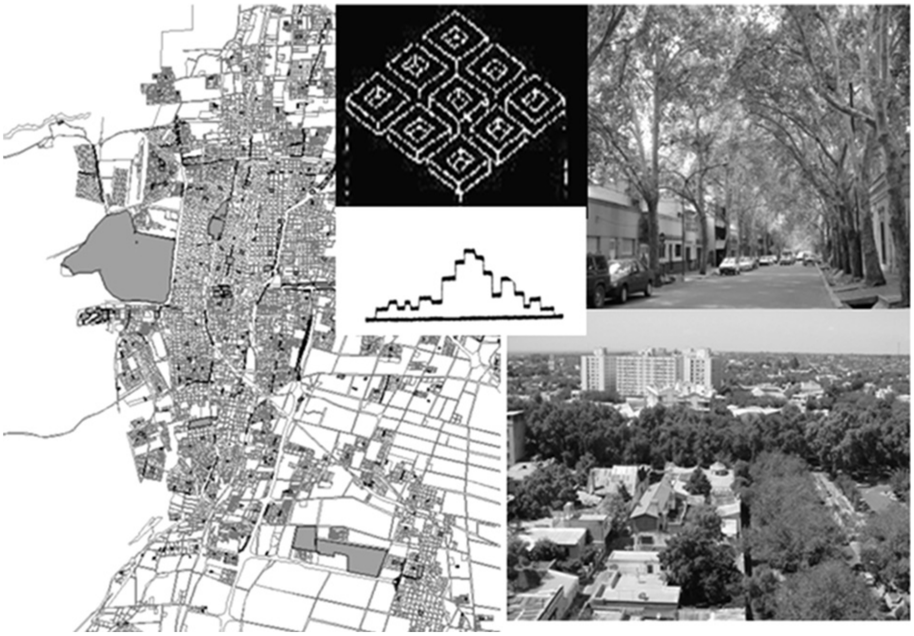

Fig. 2. Features of study city.

Fig. 3. Morphology of tree structures in urban canyons of the city studied. a) Platanus acerifolia, (b) Morus alba, (c) Fraxinus excelsior.

1 Urban canyon of 16 m forested with Fraxinus excelsior.
2 Urban canyon of 16 m forested with Morus alba.
3 Urban canyon of 16 m forested with Platanus acerifolia.
4 Urban canyon of 20 m forested with Fraxinus excelsior
5 Urban canyon of 20 m forested with Morus alba.
6 Urban canyon of 20 m forested with Platanus acerifolia
7 Urban canyon of 30 m forested with Fraxinus excelsior
8 Urban canyon of 30 m forested with Morus alba.
9 Urban canyon of 30 m forested with Platanus acerifolia

These nine cases corresponding to urban canyons located at the low density area of MMA.

Table 1
Value of H/W for the urban canyons evaluated corresponding to low building density.

Tree species	Width (Geometry parameter of road channels evaluated)					
	$W^{(a)} = 16$ m		$W = 20$ m		$W = 30$ m	
	$HB_{avg\ (a)}$ [m]	H/W	HB_{avg} [m]	H/W	HB_{avg} [m]	H/W
Platanus acerifolia	4.92	0.31	4.50	0.23	5.03	0.17
Morus alba	4.25	0.27	4.83	0.24	4.97	0.17
Fraxinus excelsior	5.03	0.31	4.43	0.22	4.72	0.16

[a] HB avg. = Building High average per urban canyon evaluated. W = Width urban canyon.

The relevance of the analysis lies in the following three elements. First, the SVF is a value for the relationship between the sky visible area and the area covered by the different elements of the environment. It is particularly important for measuring the thermal balance of cities as well as it is a key element in the generation of a heat island [21–23]. Prior studies of MMA that consider the heat island have determined that foresting low building density with First magnitude species has a negative impact over SVF. On the contrary, Second and Third magnitude species have a beneficial impact [20]. It is important remark that in high building density, during summer when thermal conditions are more compromised, there are no significant differences in the SVF between the First and the Second magnitude. In such a case, the choice of either magnitude can follow any other variable such as the longevity of a tree, its management, water adaptation, and so on [20]. This is the reason why the paper assesses only the influence of trees in the low building density. The second element is the building density. In MMA, population density ranges between 61 and 157 inhabitants per each 10 000 m^2. Inhabitants prefer individual households, which in turn leads to low building density cities, a typical Latin-American phenomenon. Approximately 80% of the building density in MMA corresponds to low-density (TOF[1] less than 2.75 m^3/m^2). Also, since the 90's, the city grew to the

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[1] Total Occupation Factor (total built-up area to total buildable area of ground level).

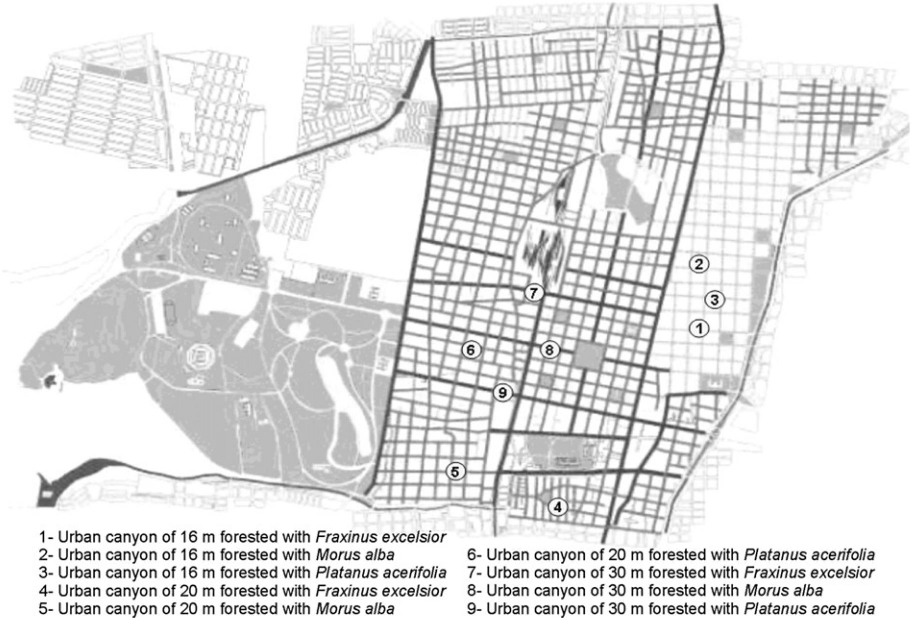

Fig. 4. Location of case studies into the city.

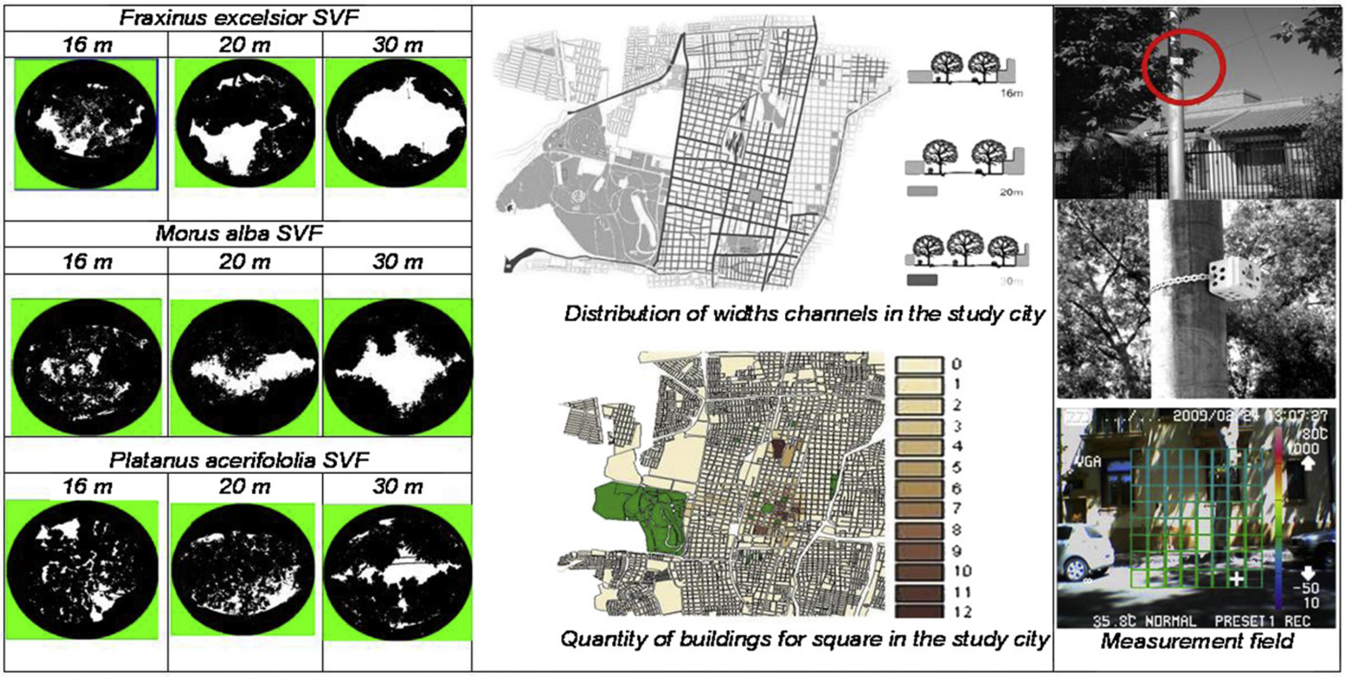

Fig. 5. Distribution of high rise buildings and widths of road channels. Field measurements and processing of sky view factor (SVF).

periphery, with a 2.2% population growth in the central area while between 26.16% and 40.09% in the periphery [24]. The buildings are defined by simple volumes, flat cover in most cases, and aligned to the municipal line.[2] They determine continuous facades along the city block whose height varies between 3 and 9 m. The predominant materiality of its forms is the result of using traditional materials and locally available technologies associated with seismic condition of the site. The combination of these factors has resulted in the conception of buildings mass (brick, concrete) finishing's textured or smooth plaster and windows with controlled dimensions.

The third element is the forest species. The most used are: Platanus acerifolia-first magnitude tree- (21.52%), Morus alba -second magnitude tree- (38.27%), Fraxinus excelsior -second magnitude tree- (19.36%). All of them are deciduous trees and represent the 79.15% of the urban forest in MMA [25]. As was mentioned in the background the tree magnitude refers to final height's tree. Platanus Acerifolia: Height 15–20 m, Morus alba: Height 8–12 m, Fraxinius excelsior: Height 8–10 m [26].

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[2] Municipal line: line limiting public and private space.

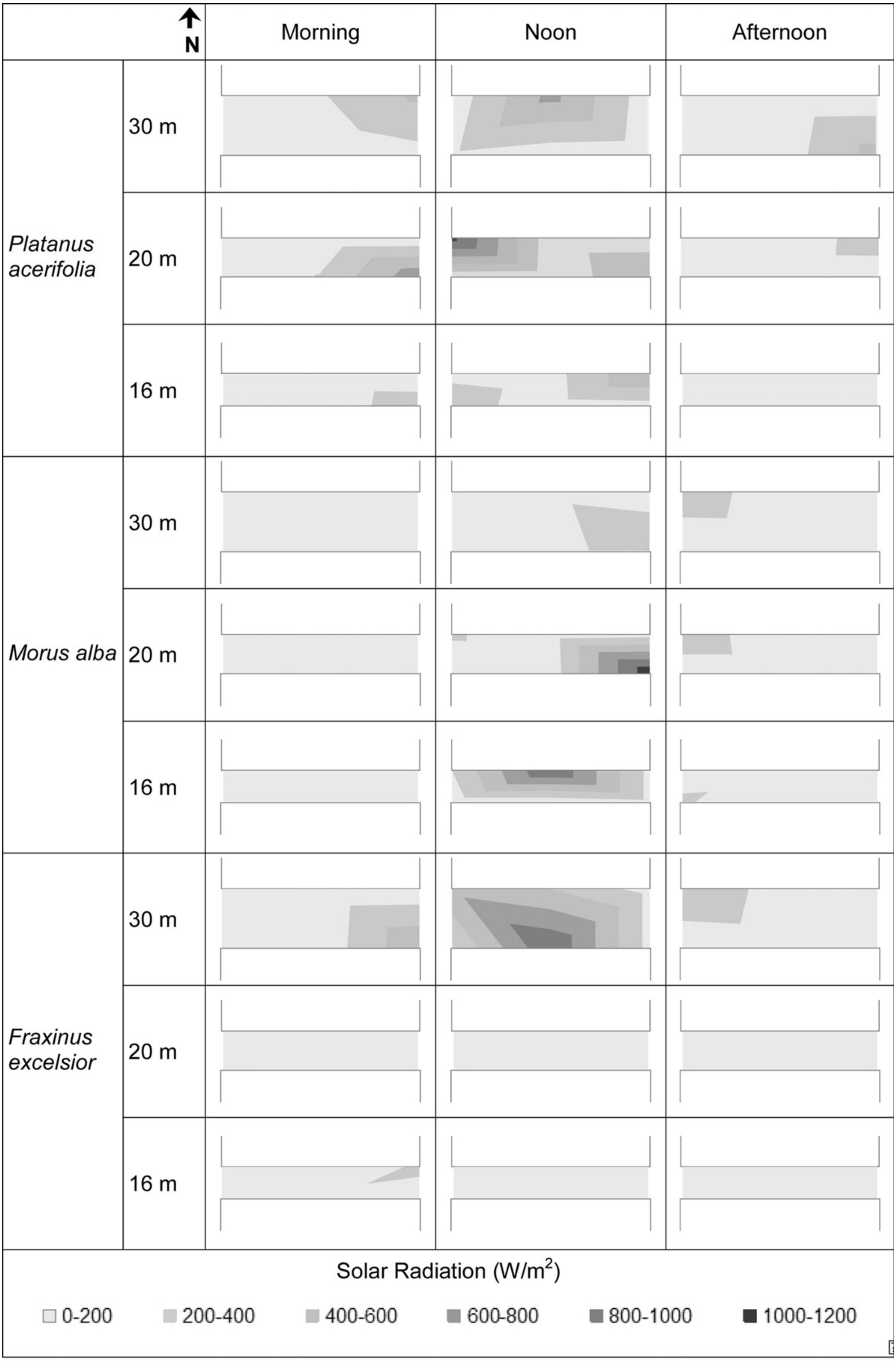


Fig. 6. Shading diagram of each case study.

Table 2
Translation of energy budget values into people's comfort levels.

Budget (W/m^2)	Sensation
Budget<-150	They would prefer to be much warmer
$-150 <$ Budget<-50	They would prefer to be warmer
$-50 <$ Budget<50	They would prefer no changes are made
$50 <$ Budget<150	They would prefer to be cooler
$150 <$ Budget	They would prefer to be much cooler

Taking all these elements into consideration, the aim was to assess the degree of thermal comfort of the road channels of low building density, forested with First and Second Magnitude species.

4. Methodology

It is based on the selection of cases, the experimental observation and the final assessment of thermal comfort conditions.

4.1. Selection of cases according to the building and forest conditions

There are three types of Urban Road Canyons (URC) in MMA, if the main variable is the street width: 16 m, 20 m and 30 m. Road channels of 16 m constitute a 25% of the whole urban framework, while 20 m represent a 70%, and 30 m are only a 5%. MMA has developed in a pyramid-shape where the high building density is in downtown- a core area of around 64 squares (approximately 640000 m^2) - that decreases progressively towards the periphery. See Fig. 2. As regards to forest configuration, as already stated, 79.15% of the species corresponds to the First and Second Magnitude, mainly Platanus acerifolia (21.52%), Morus alba (38.27%), and Fraxinus excelsior (19.36%). For the case of low building density, approximately 88.4% is mostly for species of Second Magnitude [25]. Based in previous researches related to thermal behavior of MMA [27–29], we proceeded to add the green structure and the width of URC to assess the summer thermal behavior in different urban canyons of low building density forested with First and Second magnitude species. Table 1 displays the values of H/W (height of buildings/width of road channels) in the urban canyons corresponding to low building density that were assessed. According to the H/W values, the building morphology in our cases is homogeneous and so it does not interfere with the assessment. Fig. 4 shows the distribution of the nine case studies throughout the city.

4.2. Experimental observation

The solar radiation permeability for the species under consideration was already available [26]. Nine ONSET H08-003-02 stations measuring air temperature and relative humidity were fixed to nine different spots. Sensors were put at 1.6 m height from the street level [30], inside white PVC perforated boxes that both protect sensors from radiation and allow air circulation (See Fig. 5). Data was registered during summer 2009 (January, February, and March), and it was statistically assessed to estimate the frequency distribution. The superficial temperature of both of vertical and horizontal facades was measured with an infrared thermometer OMEGASCOPE OS-XL type. For vertical facades the images were taken at 2 m of distance by means of a tripod at three different heights – 1, 1.5 and 2 m, for 20 point along the canyon; for horizontal facades the images were taken perpendicular to surface at 1 m of distance. (See Fig. 5). The solar radiation and wind speed and direction for each of the road channels was measured in the field by means of ONSET weather station. The values were taken in six point regularly distributed along the urban canyon at 1.6 m height from the street level. Fig. 6 show the shading diagram of each case study.

Hemispherical Digital Images were used to calculate the SVF of urban canyons. The images were taken in the road at the center of each urban canyon. At this point of the research we developed "PIXEL DE CIELO", accurate free software which is also easy to use for calculating the SVF from hemispherical digital images in clear-sky conditions, intense urban forest and cities with high reflectivity. It was created using DELPHI 5.0 and it runs in a Windows Environment. "PIXEL DE CIELO" obtains the SVF value of a certain urban environment from digital fish-eye JPG-format images obtained with a Nikon CoolPix digital camera with a Nikon fish-eye lens [31–33]. (See Fig. 5).

4.3. Final assessment of thermal comfort conditions

A bioclimatic evaluation that describes the effects of the thermal environment on humans requires not only a single meteorological parameter, but also the complex assessment of the effects of climate conditions and thermo-physiological values. Earlier bioclimatic indexes (Discomfort Index, Windchill, Thermohygrometric Index-THI) consider a few meteorological parameters [34–37]. Recent models based on the human energy balance equation produce the comfort indexes. One of them, the COMFA method [1] was applied to quantify the prevailing comfort conditions. We consider the metabolic rate corresponding to standing, light activity [1]. The COMFA method is a formula that measures the energy budget of a person in an outdoor environment [38–40]:

$$\text{BUDGET} = \text{M} + \text{RABS} - \text{CONV} - \text{EVAP} - \text{TREMITTED} \qquad (1)$$

Where:

M: the metabolic energy used to heat up a person; RABS: the absorbed solar and terrestrial radiation; CONV: the sensible heat lost or gaining through convection; EVAP: the evaporative heat loss; TREMITTED: the emitted terrestrial radiation.

A person is in thermal comfort when the budget approaches zero. If the budget exceeds 50, the person gains energy and feels

Table 3
Values of variables for the different cases assessed with COMFA.

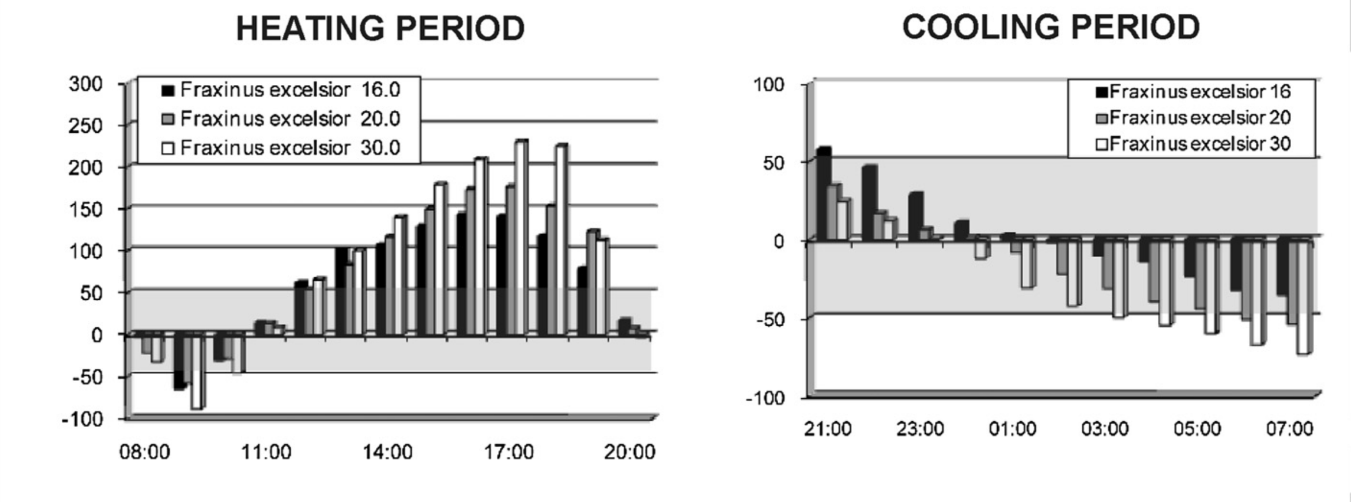
	Fraxinus excelsior			Morus alba			Platanus acerifolia		
	16 m	20 m	30 m	16 m	20 m	30 m	16 m	20 m	30 m
Summer permeability of tree species (%)	16.2			31.4			9.8		
Solar reflectance (albedo) of buildings	0.4	0.5	0.45	0.5	0.55	0.4	0.5	0.4	0.45
Solar reflectance (albedo) of ground	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Solar reflectance (albedo) of roof	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Insulation value of clothing in unit of (s m^{-1}) – Heating period –							75 (T-Shirt, long pants, socks, shoes)		
Insulation value of clothing in unit of (s m^{-1}) – Cooling period –							125 (Shirt, long pants, socks, shoes, windbreaker)		
Clothing permeability – Heating period – l m^2 s^{-1}							150 (T-Shirt, long pants, socks, shoes)		
Clothing permeability – Cooling period – l m^2 s^{-1}							65 (Shirt, long pants, socks, shoes, windbreaker)		
Metabolic rate adopted							120 W/m^2 standing, light work		

Table 4
Values of variables and energy budgets results in the different study cases.

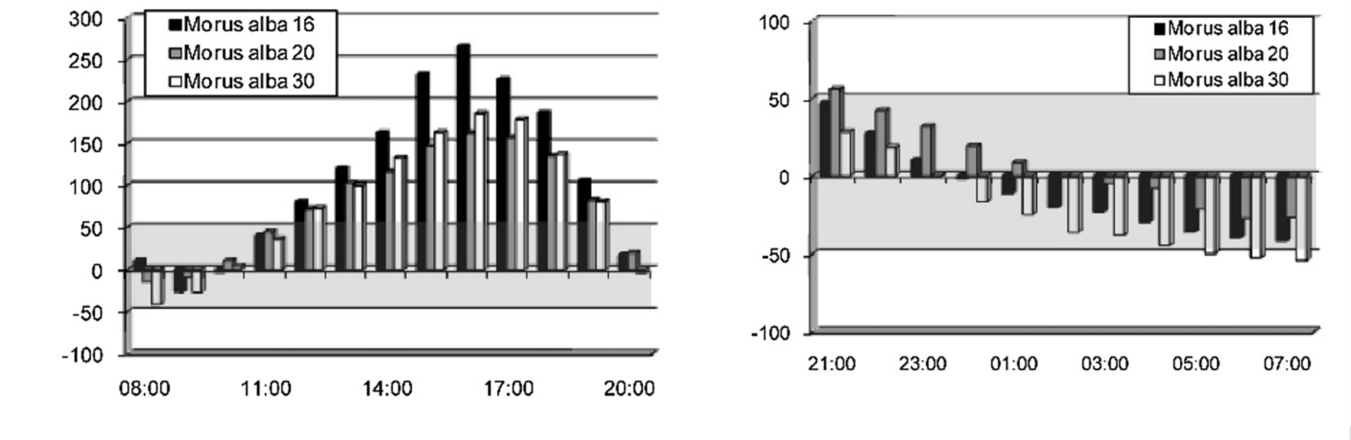
*Tsup and *Tsu are surfaces building and ground temperatures											
	Ta °C	%HR	Win m/s	SVF	Tsup °C	Tsu °C	BGD W/m^2	CONV W/m^2	EVAP W/m^2	RABS W/m^2	TRE W/m^2
Energy budget from COMFA assessment in road channels of 16 meters for a typical day.											
10:00 AM											
Fraxinius exc.	23.5	42	0.01	0.24	30	34	−30.7	162.2	271.1	524.6	439.3
Morus alba	23.5	43	0.01	0.17	27	30	−3.4	162.2	271.1	551.9	439.3
Platanus acerif.	23.2	44	0.01	0.15	26	28	−75.5	166.5	273.1	484.5	437.0
1:00 PM											
Fraxinius exc.	30.0	29	0.01	0.24	36.0	43.0	101.9	89.4	222.9	564.9	478.9
Morus alba	29.5	30	0.01	0.17	35.0	41.4	119.8	95.2	227.7	591.1	475.7
Platanus acerif.	28.4	33	0.01	0.15	32.5	35.2	33.9	107.4	237.3	522.2	468.9
4:00 PM											
Fraxinius exc.	31.8	25	0.22	0.24	37.0	46.0	143.1	69.0	204.3	575.1	490.6
Morus alba	35.7	25	0.19	0.17	40.0	47.4	265.4	25.6	155.9	622.5	515.9
Platanus acerif.	32.3	26	0.22	0.15	35.0	39.7	119.6	63.3	198.6	542.4	493.9
7:00 PM											
Fraxinius exc.	31.1	26	0.15	0.24	36.0	41.0	78.8	76.9	211.8	523.2	486.0
Morus alba	31.8	26	0.13	0.17	36.0	41.0	105.7	69.0	204.3	537.7	490.6
Platanus acerif.	31.3	25	0.15	0.15	34.4	39.0	72.3	74.7	209.7	513.2	487.3
10:00 PM											
Fraxinius exc.	27.1	25	0.56	0.24	32.5	36.0	46.2	82.5	206.1	472.9	461.2
Morus alba	26.6	27	0.48	0.17	29.0	33.0	27.2	86.3	208.7	458.2	458.2
Platanus acerif.	27.2	27	0.55	0.15	29.0	33.4	34.8	81.8	205.6	460.7	461.8
Energy budget from COMFA assessment in road channels of 20 meters for a typical day.											
10:00 AM											
Fraxinius exc.	23.7	44	0.01	0.32	28.0	36.0	−28.5	160.1	270.0	524.5	440.4
Morus alba	23.8	43	0.01	0.19	29.0	32.0	10.7	159.0	269.4	562.4	441.0
Platanus acerif.	23.9	44	0.01	0.16	24.0	28.0	−70.7	157.9	268.9	479.8	441.6
1:00 PM											
Fraxinius exc.	28.6	33	0.01	0.32	38.0	44.0	84.0	105.2	235.6	569.2	470.2
Morus alba	29.2	31	0.01	0.19	33.0	39.5	102.8	98.5	230.4	578.8	473.8
Platanus acerif.	29.3	31	0.01	0.16	31.0	36.0	46.7	97.4	229.5	521.1	474.5
4:00 PM											
Fraxinius exc.	32.9	26	0.21	0.32	35.8	43.0	162.5	67.9	203.2	592.7	491.2
Morus alba	31.9	26	0.21	0.19	35.8	43.0	162.5	67.9	203.2	592.7	491.2
Platanus acerif.	31.7	26	0.24	0.16	34.0	40.0	106.5	70.1	205.4	540.2	489.9
7:00 PM											
Fraxinius exc.	33.2	25	0.16	0.32	38.0	42.0	123.2	53.8	188.8	530.5	499.3
Morus alba	31.1	25	0.14	0.19	35.0	39.0	82.8	76.9	211.8	527.1	486.0
Platanus acerif.	30.5	28	0.16	0.16	33.0	39.0	54.0	83.8	218.0	508.7	482.1
10:00 PM											
Fraxinius exc.	25.5	33	0.61	0.32	31.0	34.0	16.7	95.1	214.4	457.1	451.1
Morus alba	26.8	26	0.52	0.19	32.0	35.0	41.9	84.7	207.6	471.1	459.4
Platanus acerif.	26.2	26	0.59	0.16	28.2	31.0	16.1	89.2	210.6	450.2	455.8
Energy budget from COMFA assessment in road channels of 30 meters for a typical day.											
10:00 AM											
Fraxinius exc.	23.1	46	0.01	0.75	29.1	37.0	−45.5	167.6	273.7	515.7	436.5
Morus alba	23.9	41	0.01	0.51	29.0	33.0	3.8	157.9	268.9	554.3	441.6
Platanus acerif.	24.2	42	0.01	0.31	25.7	28.0	−65.8	154.6	267.2	481.0	443.3
1:00 PM											
Fraxinius exc.	28.7	33	0.01	0.75	37.3	52.4	100.5	104.0	234.7	584.2	470.8
Morus alba	28.6	32	0.01	0.51	35.0	43.0	99.3	105.2	235.6	584.6	470.2
Platanus acerif.	28.8	32	0.01	0.31	33.0	37.0	43.7	103.0	233.9	526.0	471.3
4:00 PM											
Fraxinius exc.	34.1	26	0.26	0.75	42.5	52.6	209.7	43.3	177.2	599.0	505.5
Morus alba	31.9	26	0.22	0.51	39.8	50.0	185.6	67.9	203.2	615.8	491.2
Platanus acerif.	31.9	25	0.25	0.31	39.0	44.0	132.7	67.8	203.2	562.9	491.2
7:00 PM											
Fraxinius exc.	32.5	25	0.17	0.75	38.0	48.0	113.0	61.9	197.3	533.6	494.6
Morus alba	31.3	25	0.15	0.51	35.0	41.0	81.0	74.7	209.7	521.9	487.3
Platanus acerif.	31.3	27	0.17	0.31	34.4	39.0	66.9	74.7	209.7	507.8	487.3
10:00 PM											
Fraxinius exc.	26.1	28	0.66	0.75	32.0	38.0	12.2	90.6	211.5	447.8	454.7
Morus alba	27.3	28	0.56	0.51	29.0	33.0	18.4	81.0	205.0	443.5	462.4
Platanus acerif.	26.9	28	0.64	0.31	28.2	31.0	15.6	83.9	207.1	444.0	460.1

BUDGET = M+RABS−CONV−EVAP−TREMITTED.

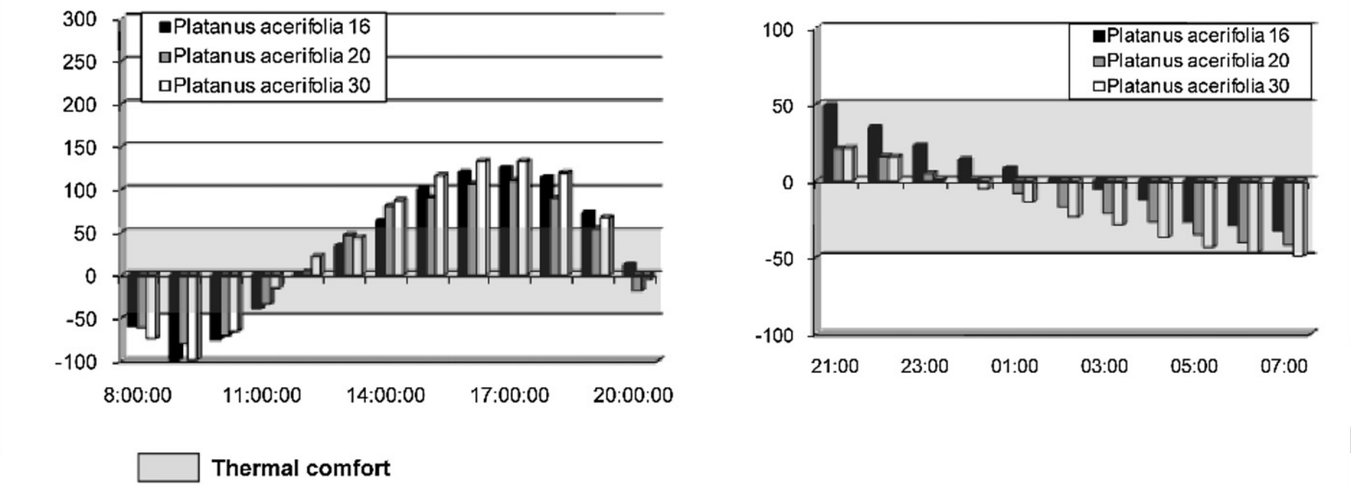
Where, M: metabolic energy used to heat up a person; RABS: absorbed solar terrestrial radiation; CONV: sensible heat lost or gaining through convection; EVAP: evaporative heat loss; TREMITTED: emitted terrestrial radiation; BGD: energy budget.



Results of energy budget for different widths of circulation channels forested with Fraxinus excelsior



Results of energy budget for different widths of circulation channels forested with Platanus acerifolia



Results of energy budget for different widths of circulation channels forested with Platanus acerifolia

Fig. 7. Results of the energy budget evaluation for each tree species.

uncomfortably warm. If the budget is negative (<-50) it feels uncomfortably cold. (See Table 2) [1].

5. Results and discussion

During January, February and March of 2009, temperature and humidity conditions of the air were continuously registered for each of the nine cases. All road channels are oriented W-E, this condition was set because these orientation present the better conditions of solar gain in the urban grid of MMA; in terms of thermal comfort during summer, this is the more severe condition [41]. The daytime hours extend from 8.00 AM to 8.00 PM while the nighttime hours go from 8.01 PM to 7.59 AM (GTM-Greenwich Mean Time-). The analysis for both periods gives a better assessment of the incidence of the different configurations over the thermal behavior. (See Table 3 for the parameters and variables considered in each of the nine cases).

See in Table 4 the values of variables and energy budgets for the cases. Fig. 7 shows the energy budget evaluation for each of the three species, and the relationships with the width of the urban frame of low building density. The forest structure with a better thermal comfort correspond urban road channels forested with

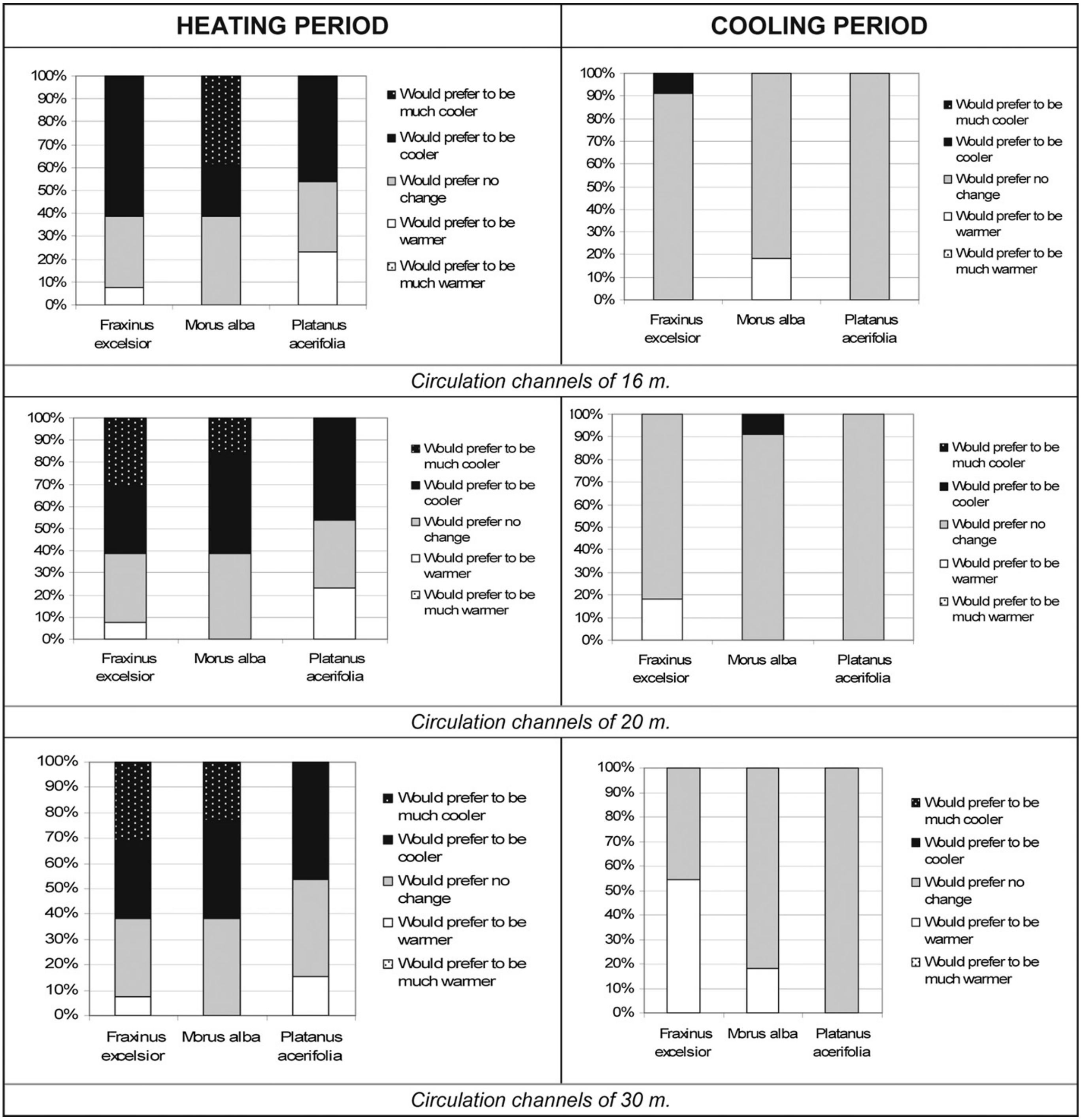


Fig. 8. Frequency of comfort conditions during heating and cooling periods.

Platanus acerifolia whose morphology has correspondence with the continuous tunnel over the street and the sidewalk. It is interesting to notice that the width of the urban frame seems to influence very little, either for heating and cooling, over the thermal comfort conditions in streets forested with Platanus acerifolia. In the case of streets forested with Morus alba and Fraxinus excelsior, the width seems to affect the thermal comfort conditions.

Fig. 7 also presents other very interesting conclusions. Unfavorable schemes are the following: 1) interrupted tunnel at the street level and homogeneous screen over sidewalk in 16 m width channels forested with Morus alba; 2) individual development of the forest without crown overlapping in 30 m width channels forested with Fraxinus excelsior.

Streets forested with Fraxinus excelsior and Morus alba has thermal discomfort from 12 PM to 8 PM when most of the people occupy the open spaces. This is critical for the space habitability. With the Platanus acerifolia, thermal discomfort prevails from 2 PM until 7 PM. Comfortable occupation then happens during the morning and the evening.

Considering the thermal transference, the worst thermal comfort conditions are those that increase the solar access, heat accumulation and superficial temperature. In this sense, the net amount of radiation that a space receives and the temperatures of the surfaces that are part of them are the result of the width and orientation of the road channel, the building density, the SVF, the tree permeability and the surfaces albedo. On the other hand, cooling possibilities are the result of the width and depth of a road channel, the SVF and the roughness of the urban-forest structure.

Results for the nine cases clearly point out to the interactions of several variables. For example, we find insignificant variations in the air temperatures. Nevertheless, we do find some important variations regarding the magnitude of the superficial temperatures, SVF, and the permeability of the species. (See Tables 3 and 4).

As for the COMFA method (equation (2)), the more significant variations of parameters referred to: 1) the absorbed radiation (RABS), and 2) the emitted terrestrial radiation (TRE). The values of them are represented in the Table 4 for all cases studied. Accordingly, Fraxinius excelsior is the most unfavorable tree for the 30 m road channels during the heating period, because its maximum radiation access possibility (See Fig. 3c). The Morus alba in 16 m channels reduce thermal comfort because their higher exposure (>SVF) related to the Platanus acerifolia. (See values in Table 4).

SVF seems to be the main variable for comfort conditions in the case of the 30 m road channels. For the 16 and 20 m road channels, the parameter CONV shows variations between the different green structures considered. In the case of 16 m wide road channels forested with Morus alba, the convective losses (CONV) diminish more than 50% related to Platanus acerifolia and Fraxinius excelsior. For 20 m wide road channels forested with Fraxinius Excelsior diminish more than 30% related to Platanus acerifolia and Morus alba. Nevertheless, the convective losses represent a little percentage in the global energy budget -about 2 to 4 %-. (See Table 4).

Respect to the evapotranspiration, it consists in the absorption of latent heat of vaporization from the ambient atmosphere to vaporize the water. The natural air-conditioning process would significantly decrease the ambient air temperature [42]. Meanwhile, the transfer of water to the atmosphere could raise the humidity in the vicinity of trees.

In other words, we could suppose that trees with height of 10 m and large crown, due to “evapotranspiration” could increase the humidity of surrounding air. But, this study did not found differences in the humidity content between the cases evaluated; this asseveration can confirmed seeing the values for the relative humidity (%HR) and evaporative heat loss (EVAP) in Table 4. Only is observed in one case, the road channels of 16 m forested with Morus alba (large crown), at 4.00 P.M., they diminish the evaporative heat loss a 22% with respect to others forest structures evaluated (Platanus Acerifolia and Fraxinus excelsior). (See in Table 4).

At international level, uncertainties exist in quantifying and valuating the ecosystem service in microclimate regulation. Firstly, at the micro level, different species and vegetation structures could affect evapotranspiration capacity- [43,44],- with impacts on microclimate. Currently, the evapotranspiration rates of only some common species have been measures and data of most urban forest species are not available. Secondly, these case studies only include the summer cooling effects of evapotranspiration. Thirdly, local meteorological and aerodynamic conditions could regulate the contributions of urban forest to local microclimate [45].

Fig. 8 displays the percentage of frequency of comfort categories according to the width of road channels and tree species. The results considering that in heating period the comfort is arise when people prefer “no change” and “to be warmer” in the comfort scale.

The Platanus acerifolia seems to be the best option for 30 m road channels, for it is in the range of the thermal comfort during more than 50% of the heating period. It stays in the comfort conditions during the whole cooling period. Its morphology offers shelter and therefore reduces the amount of absorbed radiation during the day, and it also protects from wind at night. The Morus alba follows the Platanus acerifolia for the 20 m road channels in offering a similar frequency of comfort conditions. Compared to the Platanus acerifolia, the Fraxinus excelsior in 16 m road channels has a similar frequency of comfort. (See Fig. 8).

6. Conclusions

Previous studies have estimated how diverse built forms and tree canopy coverage help to reduce the afternoon urban heat island [46]. Others have quantified the effects of green zones over the thermal comfort of cities [47] [48],. All of them have emphasized that strategic planning is vital for passive cooling.

This work takes a low building density frame in MMA, and proposes the best configuration for improving thermal comfort as well as cooling in an oasis city of hot and dry climate. It is the first assessment of the thermal comfort conditions in road channels in MMA. The three tree species were analyzed in nine situations that took into account the different morphological configurations and similar materials composition.

The results show that the absorbed solar radiation and the reemitted radiation are the most important flows into the energy budget that is used in the thermal comfort equation. Both variables depend of: a) sky view factor, witch is the result of the combination of urban, building and green structures, and b) thermophysical properties of materials because they determine its superficial temperature.

The road channels- oriented W-E - forested with Platanus acerifolia whose green structure is characterized for a continuous tunnel over street and sidewalk, has the best behavior for thermal comfort, in all cases evaluated (16, 20 and 30 m wide URC).

Besides, there is a troublesome high percentage related to the time in which an individual feels uncomfortable due to heat. The figure goes from 46% in the best case to 62% in the worst (See Fig. 8). It points out that in MMA there exists a generalized thermal discomfort, regardless of the situation. Thus to improve the thermal comfort conditions of urban open spaces we need to go beyond considering only the width of road channels and the arrangement of tree species. We need to include other variables related to the buildings materials and the space morphology, such as to add new materials into the spaces for modify surface albedo, emissivity, and heat accumulation. Associated to the second variables -space morphology- would be interesting revise intervals of trees plantation, setbacks from municipal building line, and so on.

Taking into account the urban problems of the city under study, it is necessary to settle the comfort conditions with the possibility of nocturnal cooling. During the daytime the solar radiation control is a key to getting comfort conditions. During the nighttime, sky vision is needed for radiative cooling. In addition, the forest structure combined with the urban morphology increase soil roughness and reduces the convective cooling. Therefore it is necessary to encourage those combinations of forest structure and urban morphologies that benefit both processes.

Conforming to our assessment, the best combinations are: 1) First Magnitude species such as the Platanus acerifolia for 30 m road channels 2) Morus alba for 20 m road channels and 3) Fraxinus axcelsior for 16 m road channels.

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