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PRINCIPAL COMPONENT ANALYSIS OF THE URBAN BUILDING MORPHOLOGY OF THE METROPOLITAN AREA OF MENDOZA, ARGENTINA[1]

ANÁLISIS DE COMPONENTES PRINCIPALES DE LA MORFOLOGÍA URBANO EDILICIA DEL ÁREA METROPOLITANA DE MENDOZA, ARGENTINA

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Las ciudades insertas en zonas áridas afrontan una serie riesgos que amenazan su sostenibilidad, al ser impactadas por los efectos del cambio climático y la urbanización, y consecuente inequidad de consumos y agotamiento de los recursos naturales. Existen muchas variables que determinan la forma urbano-edilicia, las que a su vez influyen en el consumo de energía en las ciudades. Por ello, el objetivo de este trabajo es condensar la información aportada por las variables morfológicas urbano-edilicias en solo algunas variables o combinaciones de ellas para las manzanas urbanas ubicadas en los seis departamentos del Área Metropolitana de Mendoza (AMM). Metodológicamente, se computaron datos cuantitativos de la distribución espacial de las variables urbano-edilicias, se calcularon sus correlaciones y se aplicó un análisis de Componentes Principales para sintetizar la cantidad de variables. Los resultados identifican como principales variables de la primera componente principal -en cinco de los seis departamentos del AMM- a la densidad edilicia, la separación edilicia y el Índice de Vegetación de Diferencia Normalizada (NDVI); las dos primeras relacionadas al ambiente construido y la tercera, a la vegetación. Al incorporar datos del arbolado urbano disponibles solo para el departamento de Capital, los resultados incluyen las variables magnitud, completamiento y trasmisividad del arbolado, junto a las ya identificadas en las primeras tres componentes. Los hallazgos del trabajo brindan información sobre las variables urbano-edilicias representativas de la ciudad oasis que permitirán a futuro establecer prioridades de intervención considerando un número reducido de variables sintéticas, a fin de proponer estrategias de eficiencia y generación energética.

Palabras clave: morfología urbano-edilicia, análisis de Componentes Principales, desarrollo urbano sostenible.

Cities located in arid areas are facing several risks that threaten their sustainability due to the effects of climate change and urbanization, and the resulting consumption inequality and depletion of natural resources. There are many variables that determine the urban-building form, which, in turn, affects energy consumption in cities. Therefore, the goal of this work is to condense the information provided by the urban-building morphological variables into just a few variables or combinations for the urban blocks located in the six departments of Mendoza's Metropolitan Area (MMA). Methodologically, quantitative data of the spatial distribution of urban-building variables were considered, their correlations were calculated, and a Principal Component Analysis was applied to synthesize the number of variables. The results identify the Building Density, Building Separation, and Normalized Difference Vegetation Index (NDVI) as the main variables of the first principal component, in five of the six departments of the MMA. The first two are related to the built environment, and the third is to vegetation. By including data on urban tree cover, available only for the Capital department, the results include the tree-cover magnitude, completeness, and transmissivity variables, together with those already identified in the first three components. The findings of the work provide information on the representative urban-building variables of the oasis city that will allow, in the future, establishing intervention priorities considering a reduced number of synthetic variables, to propose efficiency and energy generation strategies.

Keywords: urban-building morphology, principal component analysis, sustainable urban development

I. INTRODUCTION

Currently, most of the world's population lives in urban centers. Cities inserted in drylands, which have adapted historically to the environment and the lack of resources, face more profound challenges with land and soil degradation, the water crisis, extreme climatic events, disparate expansion models, and consumption that threaten the habitat's sustainability and deepen inequities.

Based on these problems, this research is justified by the relevance the urban-building form issue has gained in recent decades for sustainability (Bibri, 2021; Burton, Jenks & Williams, 2013; Jabareen, 2006; Jenks, Kozak & Takkanon, 2013; United Nations, n/d; Sharifi, 2021), and for its influence on energy consumption (Owens, 1986), with a special focus on the quantitative analysis (Artmann, Kohler, Meinel, Gan & Ioja, 2019).

Contemporary research on urban morphology intersects with the themes of smart cities, computational geometry, and information management, to explore the urban form through large use collected and/or generated datasets (Boeing, 2021). This allows applying statistical methods, among which Principal Component Analysis (PCA) stands out (Johnson & Wichern, 1998). Methodologically, there is a history of spatial studies that have applied Principal Component Analysis (PCA) to evaluate the characteristics of neighborhoods and identify territorial differences in certain variables (Maiullari, Esch & Timmeren, 2021; Wu, Peng, Ma, Li & Rao, 2020) or to identify the urban form and understand the transformations induced by expansion processes (Lemoine-Rodríguez, Inostroza & Zepp, 2020). Meanwhile, other background information from PCA analysis connects the urban form to vegetated spaces and ecosystem services (Grafius, Corstanje & Harris, 2018).

The study on an urban scale, compared to the building scale, is more complex and demanding in terms of time and resources, especially in highly forested cities. The local challenges include overcoming information segmentation and identifying and analyzing the urban-building form from the available data.

In this work, the Mendoza Metropolitan Area (MMA) was chosen as a case study. It is located on an urban plot with orthogonal block grids, of approximately 100m x 100m, and a cardinal deviation of 12º to the east. Over time, its development has been heterogeneous, generating denser central areas and others characterized by dispersed growth, expanding into the periphery with marked morphological variations.

In previous works on the MMA, partial analyses of some urban-building variables have been made and presented. The objective proposed here is to determine the relationships between urban-building morphological variables and identify from the group of variables, those that most differentiate the blocks within each department and for the Mendoza Metropolitan Area by implementing a PCA. The goal is to obtain representative combinations of this oasis city's urban-building variables.

II. THEORETICAL FRAMEWORK

Urban-building morphology has been studied for its effects on the urban microclimate, outdoor thermal comfort, building energy behavior, solar availability on north facades and roofs, solar gains, and wind direction and speed (Chen, 2021; Nowak & Greenfield, 2018). The theme presents distinctive features in arid urban environments since energy balance is dependent on the solar irradiance received by the morphologies (Oke, 1988). Articles on the relationship between urban-building form and energy have pointed out key indicators in energy demand (Al-Saaidy, 2020; Biljecki & Chow, 2022; Chen, Han & de Vries, 2020). The gaps in knowledge point to the need to recognize essential urban-building variables, reveal their correlations and develop rigorous tools to implement statistical models that avoid endogeneity (Quan & Li, 2021). In this sense, the Principal Component Analysis tool is optimal for capturing the variables that express most of the total variability in the data, examining the correlations, and reducing analysis by defining new synthetic variables, called Principal Components (PC) (Johnson & Wichern, 1998).

From a historical and local perspective, the form of the AMM has inspired several investigations that have determined diverse spatial processes (Bórmida & Dabul, 2014; Ponte, 2008). The study of Mendoza as an "oasis city" proposes achieving the environmental conditioning of a desert sector through a configuration of a vegetation architectural structure and outlines nine basic components within the city's matrix at the beginning of the last century: layout, green squares, parks, avenues-streets-sidewalks, canals, groves, continuous facades, articulated volumes, yards, and orchards (Bórmida, 2014). Numerous authors have also focused on urban expansion trends and the impact of growth in the last 50 years on the MMA (Bernabeu,

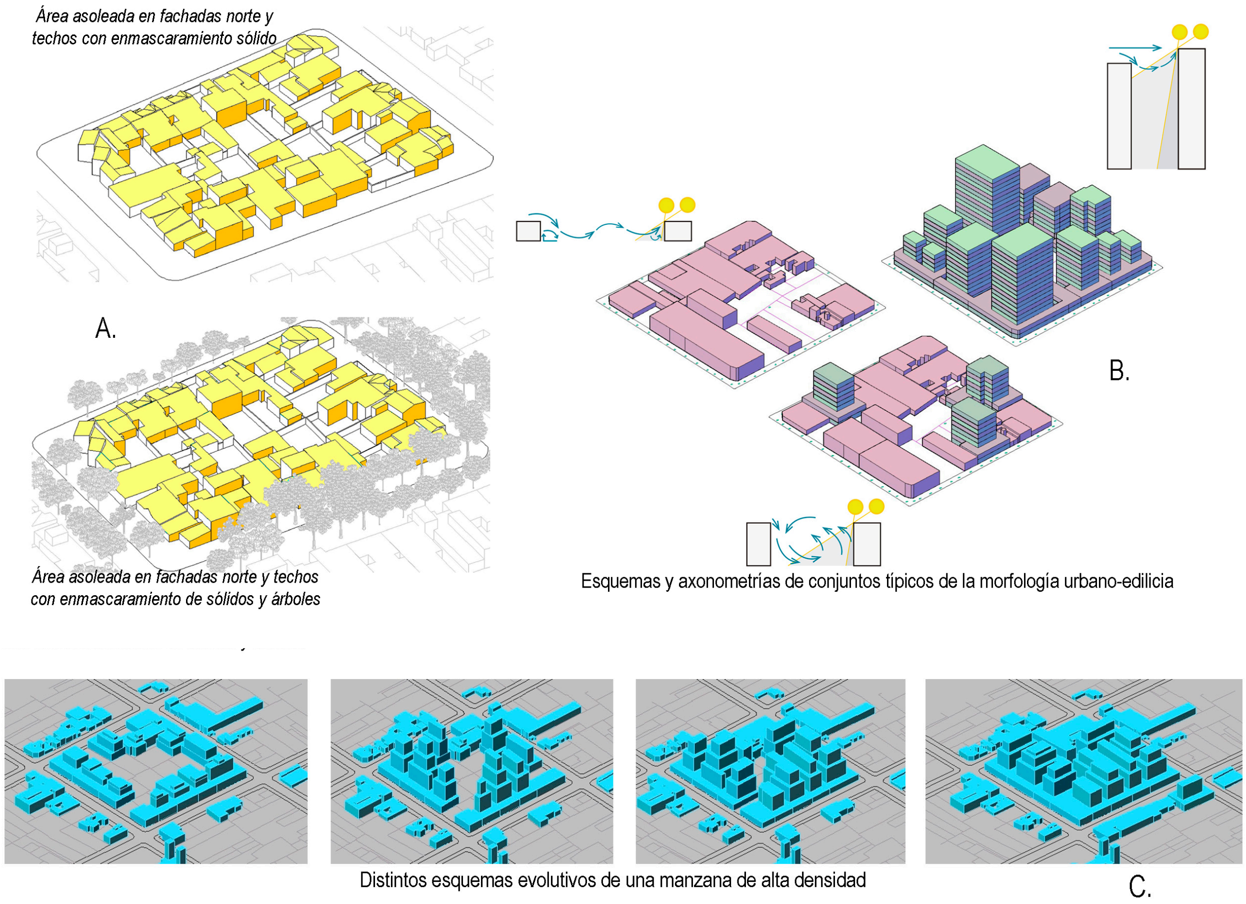


Figure 1. Layouts and axonometries of the urban-building morphology of MMA's blocks. Source: A. Prepared by Mariela Arboit; B. Graphic collaboration by Cecilia Camino; C. Mesa, Arboit, Herrera & de Rosa, 2010.

Navarrete & Ávila, 2019; Gray de Cerdán, 2005; Gudiño, 2018; Molina, Arboit, Maglione, Sedevich & Mutani, 2020; Pastor, Marchionni & Torres, 2020). In addition, work has been done on variables that consider urban and building morphology related to energy behavior (Ganem, Balter & Alchapar, 2021; Mesa & de Rosa, 2001) (Figure 1), as well as some characteristics of the urban-building form, but detailed analysis of the relationships between these variables is still pending.

III. CASE STUDY

The Mendoza Metropolitan Area (MMA) is located in the central-western region of Argentina. It is home to approximately 1,193,327 inhabitants and contains several territorial characteristics: oases and non-irrigated lands, and urban and rural-urban portions. The area has a marked aridity as a result of low rainfall, high levels of sunshine, and significant seasonal and daily temperature variations. The average annual relative heliophany is high - above 8 hours a day-, and the cloud cover has annual values of less than 40% of the sky covered, with an average annual global solar radiation of 18.06 MJ/m^2 day. The annual heating degree-days on a 18ºC base are between 1300ºC and 1500ºC, and those of cooling on a 23°C base, are at 163°C.

The MMA is the result of a conurbation of 6 municipalities (Capital, Godoy Cruz, Guaymallén, Las Heras, Luján de Cuyo, and Maipú) that were physically laid out around Mendoza (Figure 2). In recent decades, the urbanized area has undergone changes, growing at a higher rate than the urban population. If this trend continues, an even greater energy-environmental deterioration of the habitat is foreseeable (Molina *et al.*, 2020).

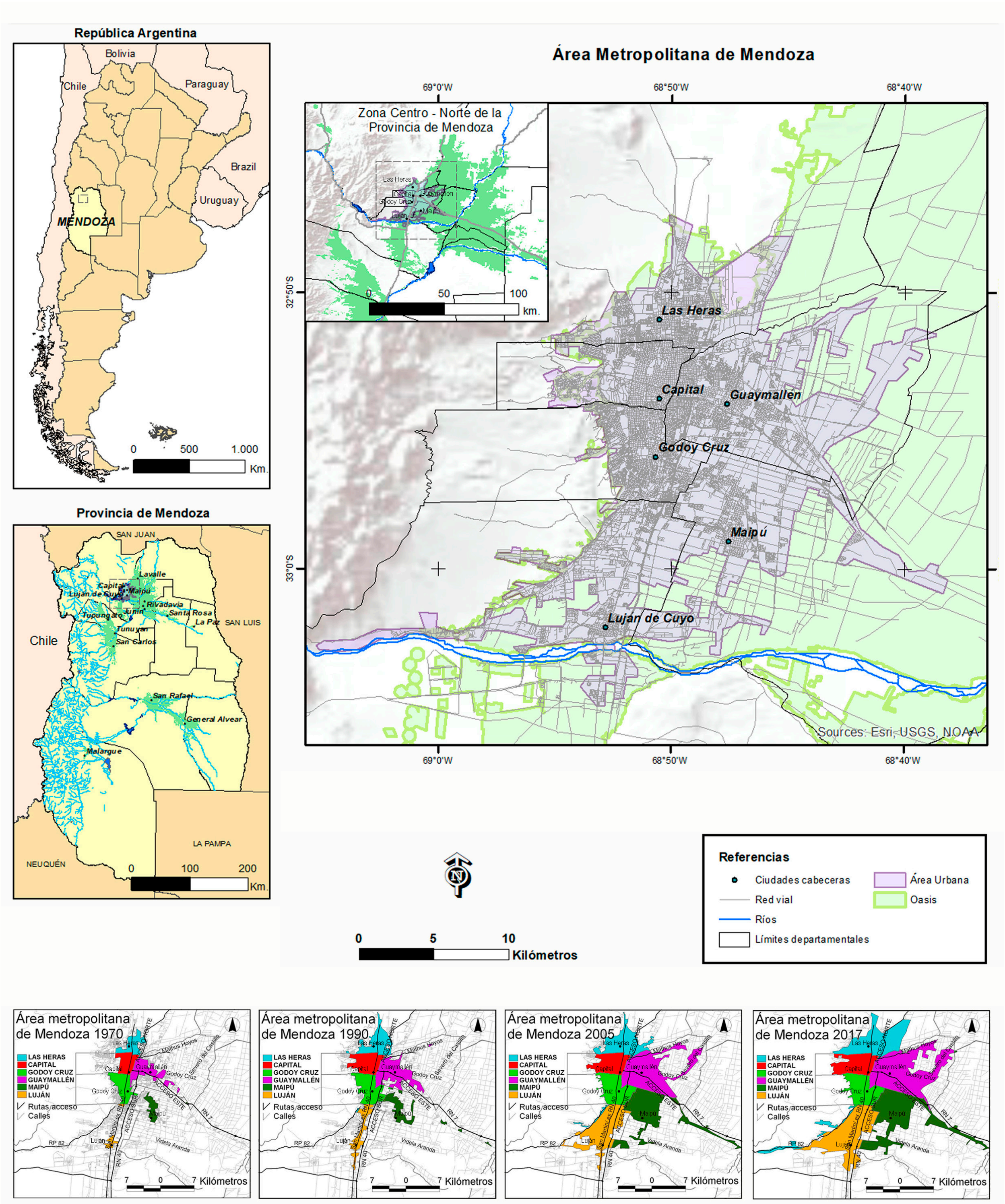


Figure 2. Location of the Mendoza Metropolitan Area and change of urban form from 1970 to 2017. Source: Prepared by Ricardo Cohn, based on Molina et al. (2020).

IV. METHODOLOGY

Although the methodology used in this research has already been partially reported in previous publications, it is necessary to present a synthesis to help understand the results of recent tasks that are presented for the first time here. The already completed stages have been:

1. Collection of available cadastral information and its mapping for the entire MMA in geographic information systems (GIS), using urban-building data (General Directorate of Cadastre (n/d); Mendoza Infrastructure Spatial Data [IDE], 2022), satellite images (United States Geological Survey [USGS], 2018) and georeferenced census of public tree cover 2012 (Capital Municipality, n/d).

2. Description of the group of urban and building morphology variables related to a greater or lesser extent with energy behavior.

Urban-building variables

1. Block (BlockF): proportion of the sides of approximately rectangular apples.

2. Block orientation (BlockO): the angle formed by the longest side of the block and the N-S line.

3. Street Width (SW): distance between blocks (with null data correction and excluding unbuilt blocks larger than 30,000 m^2).

4. Normalized Difference Vegetation Index (NDVI): normalized quotient between spectral bands (red and near-infrared) from the monthly satellite images, for the 2013-2017 period (considering annual averages, winter, and summer).

5. Urban tree cover: spatial distribution of the four most common species per block that includes three subgroups of variables explained below: Magnitude, Completeness, and Transmissivity. Magnitude: its value depends on the size and physical characteristic of the specimen; Completeness: number of tree specimens in the block's perimeter compared to the admissible number in the same block taking into consideration the appropriate separation between trees, in percentage; and Transmissivity: describes the portion of average global radiation that passes through branches and foliage, compared to the unobstructed amount in the same period. The three subgroups of variables are available only for the Capital department that has a survey of urban tree cover.

6. Building footprint (BF): the ratio between the built building area on the ground floor and the total surface area.

7. Total building factor (TBF): the ratio of the total built area and the total surface area, expressed as a fraction.

8. Building height (BH): average height of constructions calculated as the number of floors by their average height (3 m). Here the average value of the block was calculated.

9. Building separation (BS): distance between buildings calculated as the average distance of a building within a radius of 100m in relation to the 30 nearest buildings.

10. Building height/building separation ratio (BH/BS): quotient between the building height and the average separation of the buildings in the setting.

11. Building orientation (BO): predominant orientation of the building; direction of the longest facade.

12. Building density (BD): the ratio between the built
volume on the block and the area of the block (m^3/m^2).

13. Surface/volume ratio (SExp1/V and SExp/V): ratio between the exposed area (vertical + horizontal) of a building envelope and its volume (m^2/m^3) which considers, for SExp1/V, one horizontal surface (roofs) and, for SExp/V, two horizontal surfaces (floors and roofs).

3. Calculation of urban-building variables. The urban block (delimited by streets on all sides) was considered as a unit of study. 9,320 of the 10,390 urban blocks of the MMA are contemplated for the study (once the blocks with missing or erroneous data have been eliminated). Subsequently, the results are calculated and mapped throughout the MMA. For 880 blocks of the Capital department, a detailed study is expanded by incorporating the variables of 48,419 urban trees. Figures 3 and 4 show the cartography of two variables chosen as representative: building separation and building density.

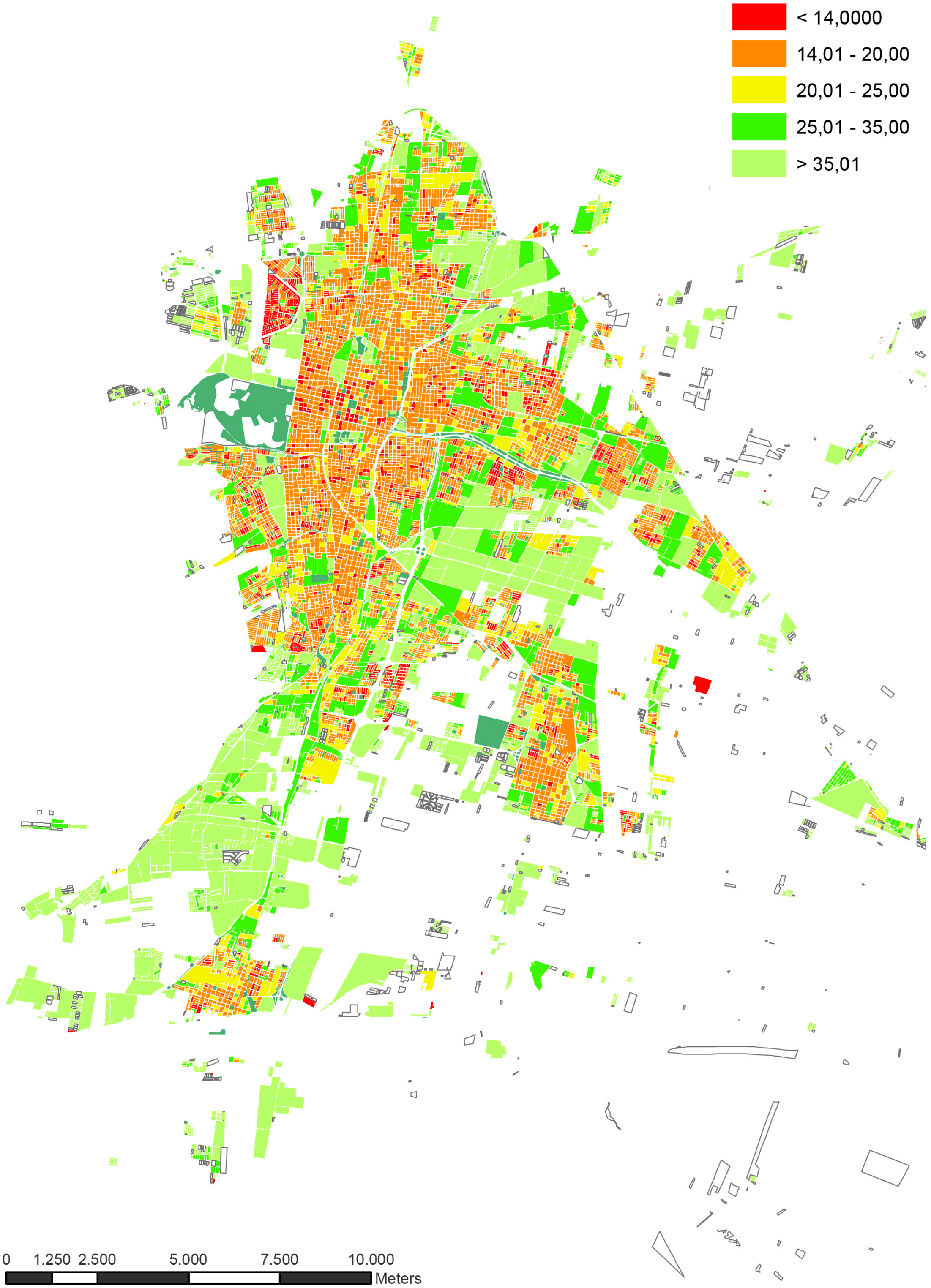


Figure 3. Building Separation in the urban blocks of the MMA. Source: Preparation by Manuela Fontanive.

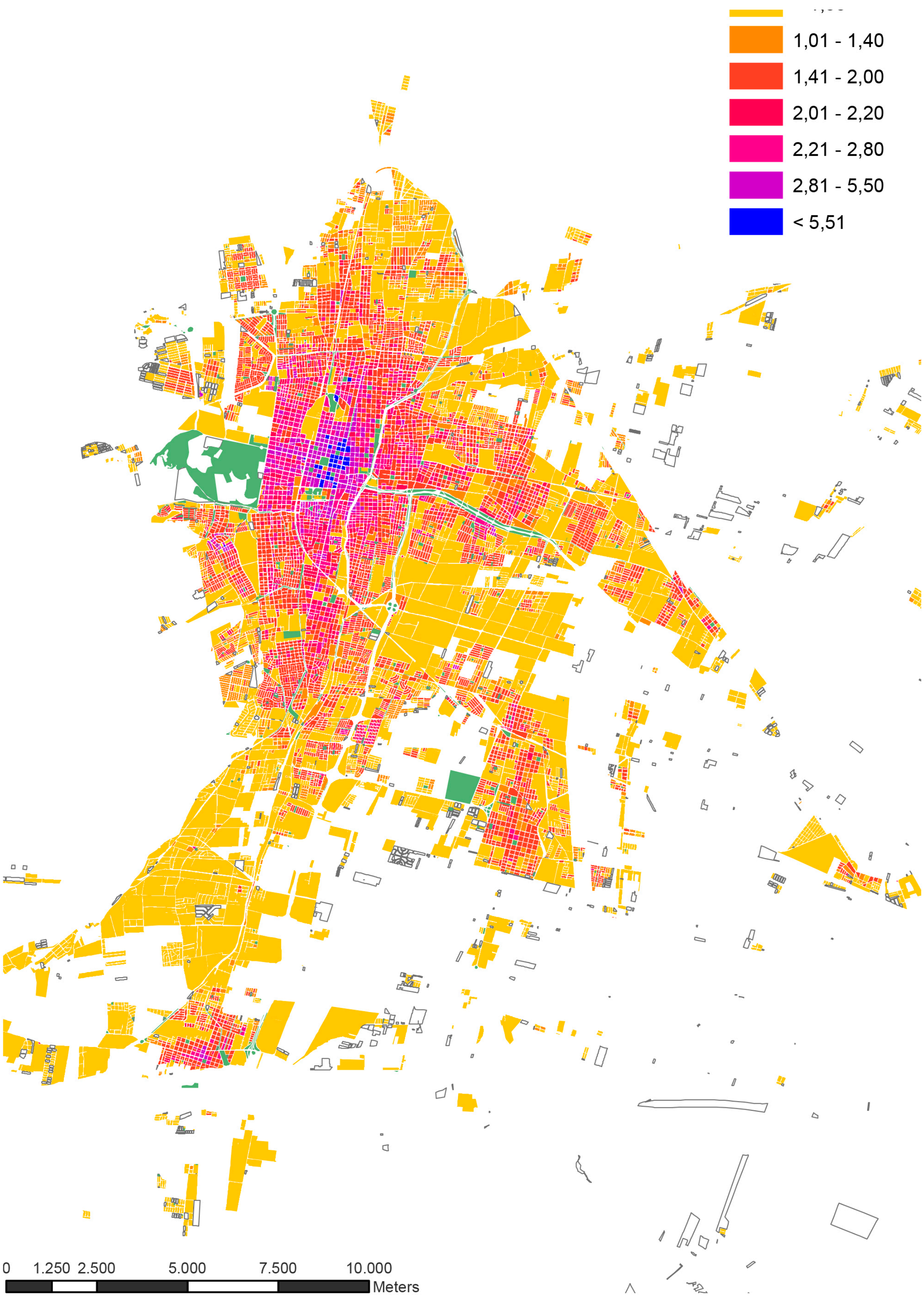
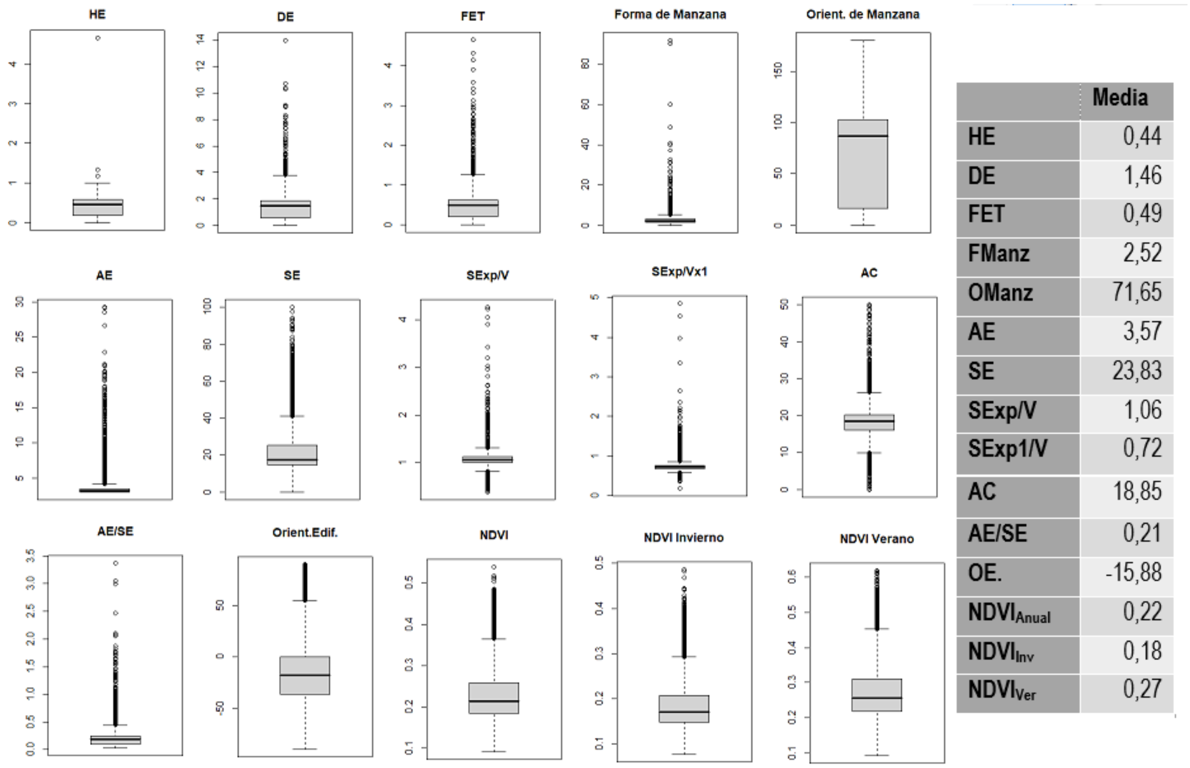


Figure 4. Building Density in the urban blocks of the MMA. Source: Preparation by Manuela Fontanive.



	Media
HE	0,44
DE	1,46
FET	0,49
FManz	2,52
OManz	71,65
AE	3,57
SE	23,83
SExp/V	1,06
SExp1/V	0,72
AC	18,85
AE/SE	0,21
OE.	-15,88
NDVI$_{Anual}$	0,22
NDVI$_{Inv}$	0,18
NDVI$_{Ver}$	0,27

Figure 5. Summary measurements of the urban-building variables in the MMA. Source: Prepared by Dora Maglione.

Below, the tasks carried out recently are described:

4. Database integration. The set of urban-building variables was integrated into a single database.

5. Correlation analysis. To inspect the strength of associations and avoid collinearity, the (Pearson and Spearman) correlations were calculated for each urban block. For the subsequent analysis, strongly correlated variables were eliminated (Spearman correlation coefficient >0.80).

6. Principal Components Analysis. All metrics with Z transformation were centered and scaled to make them comparable, ensuring that they had the same contribution to subsequent models. To reduce the number of variables, a Principal Component Analysis was applied, arguing that a high degree of variance can be captured in a smaller number of dimensions than with the original data. These new Principal Components (PC) are uncorrelated. The Kaiser (1960) criterion was also used for the selection of the PC (Jolliffe, 2002), retaining only the components with values greater than 1 and for each of them, variables that had moderate to high correlation with the PC were prioritized ((|r|> 0.45).

7. Using the estimated PC for each block, the averages by department, were compared using a variance analysis with heteroscedasticity by department, and the Fisher test was applied for peer comparison.

V. RESULTS

Figure 5 shows different summary measurements of the urban-building variables.

Correlations between variables.

When interpreting the p-values of the Pearson and Spearman tests, there is a correlation between variables (Figure 6). To ensure a set of non-highly correlated urban building variables, BF, TBF, BH/BS, NDVI$_{summer}$, and NDVI$_{annual}$ were eliminated, although it is noted that they are just as representative as those that are correlated.

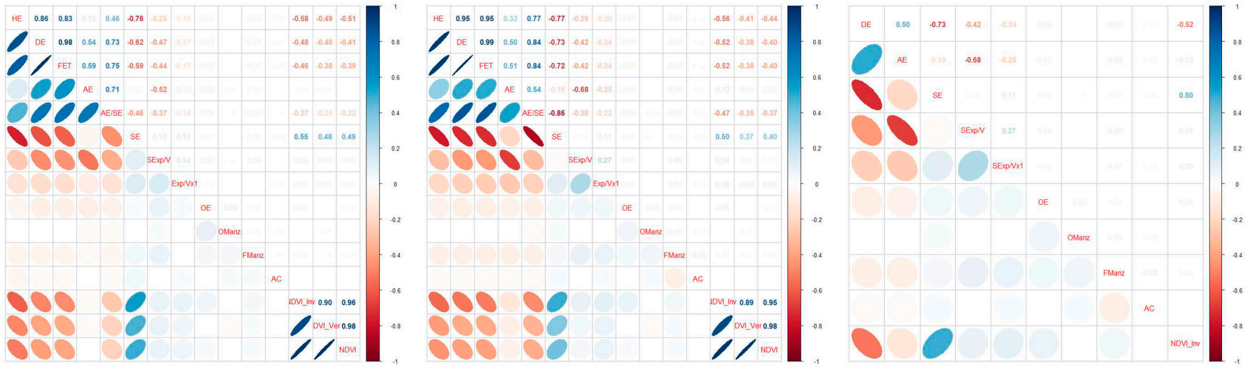
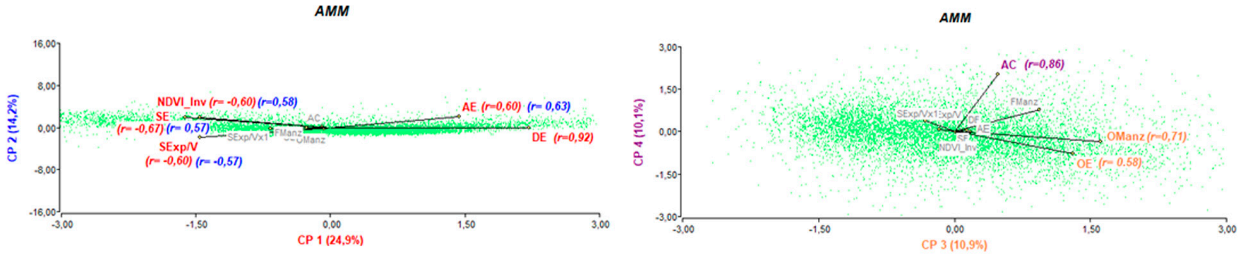


Figure 6. Pearson correlation coefficients (left) and Spearman (center and right). Source: Prepared by Dora Maglione.



CP1= -0,43SE +0,58DE +a

CP2= -0,50NDVIinv +0,53AE +0,47SE -0,48SExp/V +a

CP3= 0,68OManz +0,56OE +a

CP4= 0,91AC +a

Figure 7. PC for MMA, significant correlations, and resulting equations. Source: Prepared by Dora Maglione.

Principal Component Analysis.

In the analysis of the results for the MMA, the first two components mainly evaluate the building density, building separation, building height, NDVI, building separation, and surface/volume ratio (SExp/Vol) variables. PC1, which groups blocks with high building density and low building separation, on one side, and blocks with low building density and high separation on the other, reveals a 25% variability between blocks, while PC2, has a 14% variability. The third component (11% of the variability) mainly evaluates the orientation of the building and the block, and the fourth component does so for the width of the street (Figure 7).

The analysis by department indicates that there is a coincidence in the first two components, although the importance is different depending on the department. For all departments, the building density is represented in PC1, and the building separation, in five of the six departments in MMA where the NDVI also appears as important (this groups at one end, blocks with high building density and low building separation and NDVI values, and at the other, blocks with high building separation and NDVI values and low building density values). For these departments, PC2 is characterized by the variables “building height” and “surface/volume ratio” (SExp/Vol), grouping high building height values with low SExp/Vol (Figure 8). The analysis of the other components of the different departments reveals that there is a coincidence in the building orientation, block orientation, and block form variables.

In the case of Capital, the characterization of form is different. The results show that the first four variables are building (building density, building height, surface/volume ratio -SExp/Vol-, and building separation) and the fifth is NDVI (considering PC1 and PC2). PC3 is associated with the orientation and form of the blocks, and PC4, with the width of the streets (with approximately 10% variability).

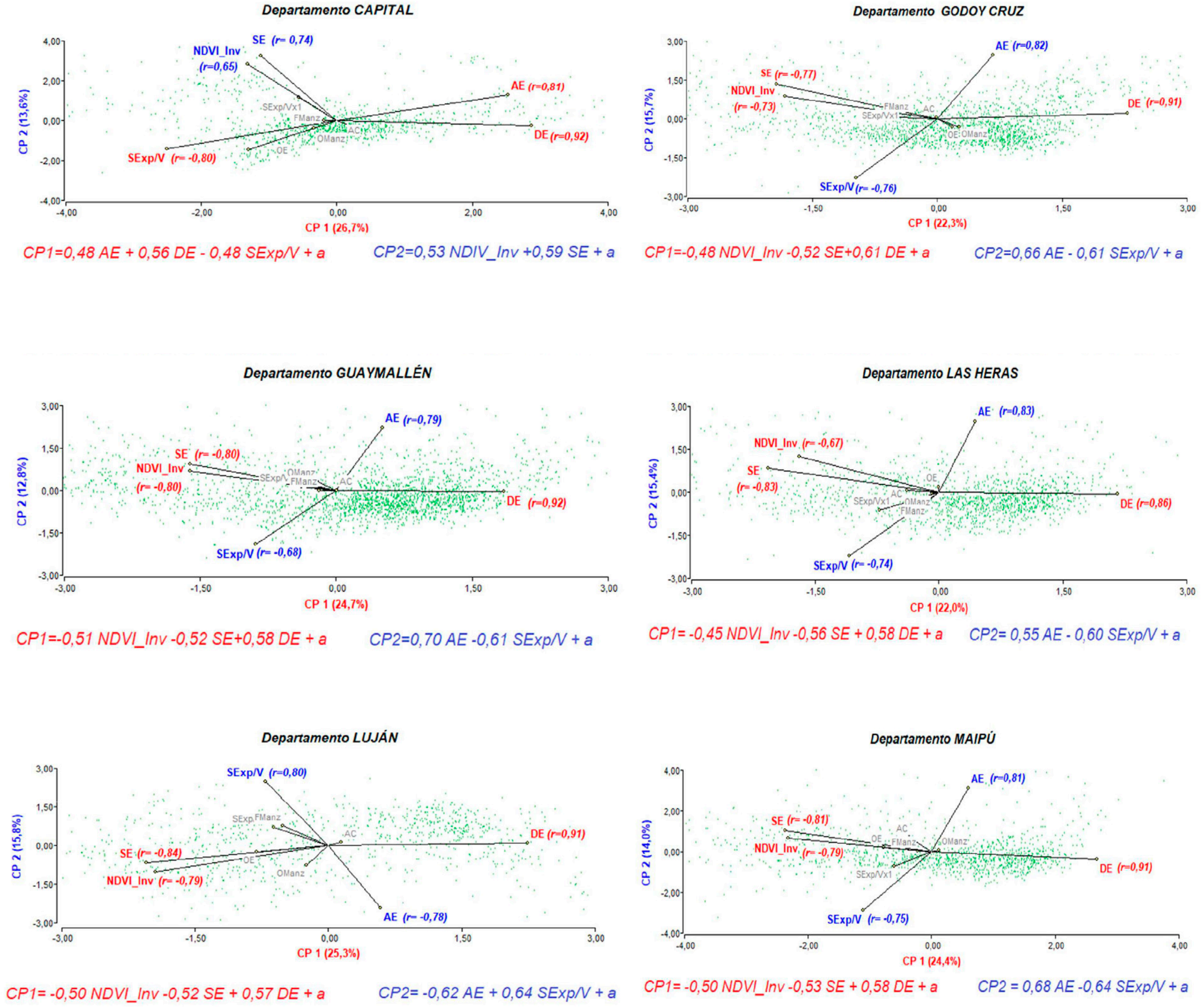


Figure 8. PC by department, significant correlations, and resulting equations. Source: Prepared by Dora Maglione.

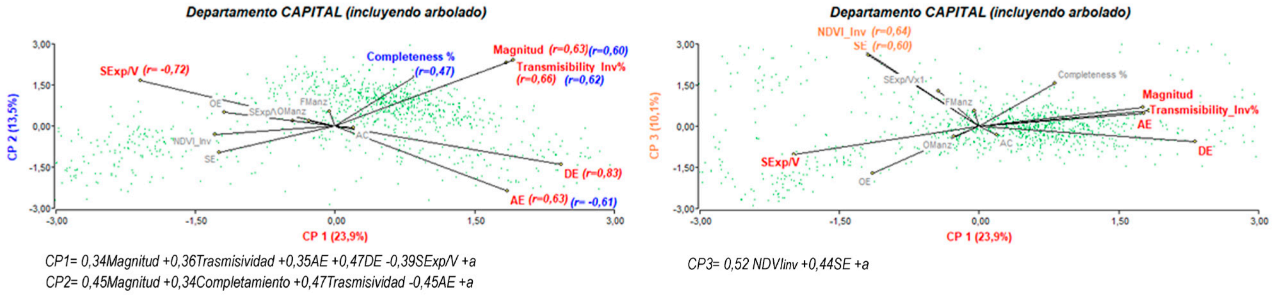


Figure 9. PC for Capital including urban tree cover variables, significant correlations, and resulting equations. Source: Preparation by Dora Maglione.

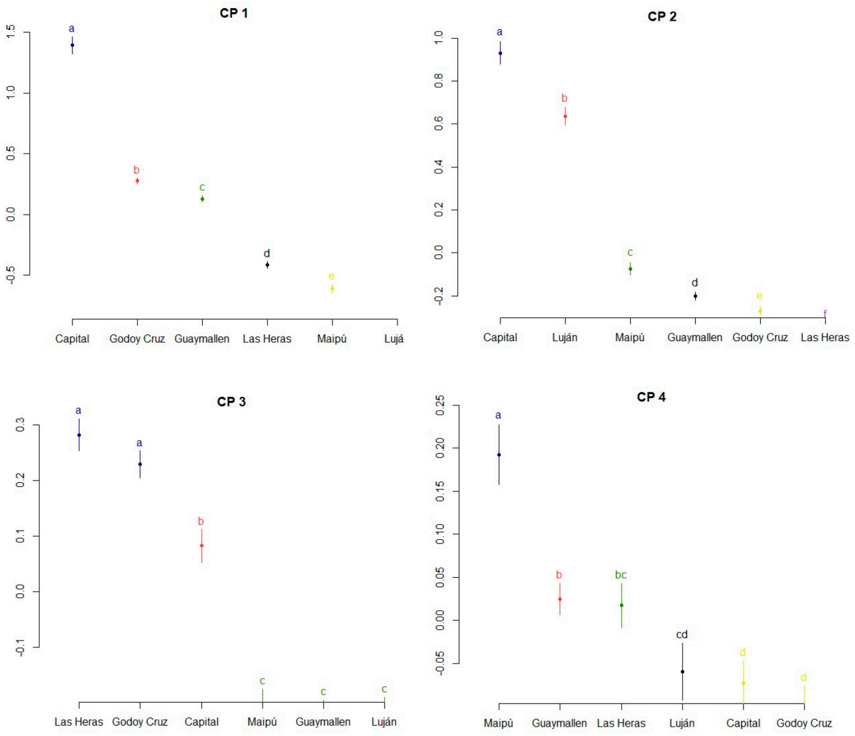


Figure 10. Mean difference test for each PC in the MMA (Departments that share the same letters indicate statistical equality). Source: Prepared by Dora Maglione.

Figure 9 presents the results for the Capital department, incorporating the Magnitude, Completeness, and Transmissivity of the trees. The highly correlated variables were excluded from the study: total building factor, $\text{NDVI}_{\text{summer,}}$ and $\text{NDVI}_{\text{annual}}$.

The results show 5 PCs that explain the differences between blocks. These reach an accumulated proportion of 64%. PC1 records 24% variability. The variables that best represent the PC1 are building density, area/volume ratio (ACP/Vol), transmissivity, building height, and tree magnitude. In PC2, the three urban tree cover variables and building height can be observed.

Finally, in Figure 10 the values of the 4 PC are compared for general analysis (MMA). It is noted that there are differences between the average values of the blocks between departments. For PC1, the average values are different in all departments: the highest corresponds to Capital and the lowest, to Luján. Capital is the one with the highest building density and lower building separation (both combined), while Luján has a lower building density and greater building separation. In the case of PC2, the same thing happens, all the average values are different: the largest corresponds to Capital and the smallest, to Las Heras. In PC3, there are 3 groups.

VI. DISCUSSION

The results of this research show coincidences with the historical perspective, with the relevant theoretical-conceptual background on the urban form and with the presence of elements for the environmental conditioning of a desert sector (Bórmida, 2014) (Figure 11).

For the MMA, the first Principal Component (PC) identifies building density and building separation, while for five of the six departments of the MMA, the NDVI variable is added to these. Of these three variables, it is worth detailing the following:

-The blocks with high building density represent a low proportion in the MMA. These blocks are more energy efficient than blocks with independent single-family homes

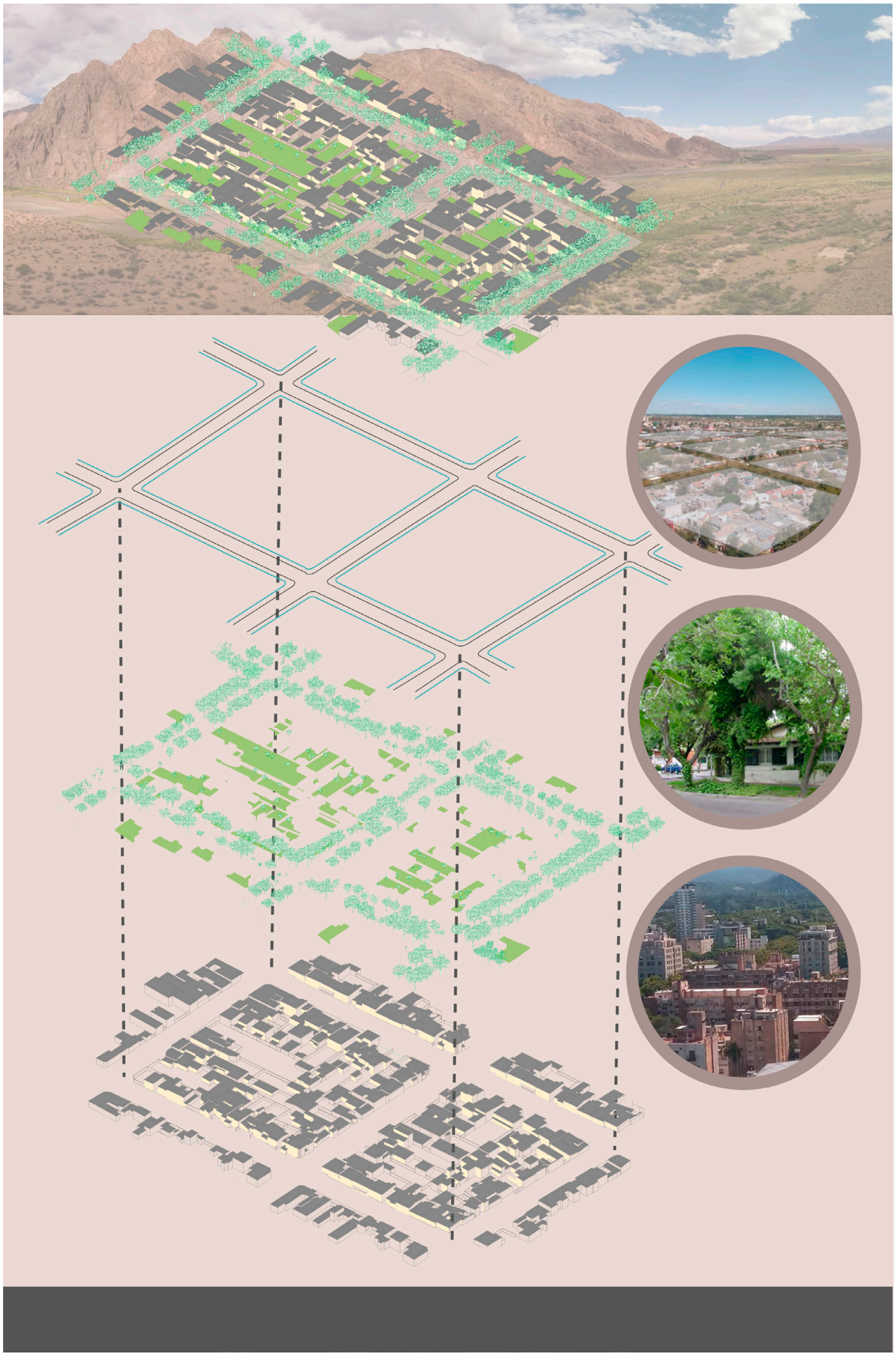


Figure 11. Analysis overlay outline. Source: Preparation by Cecilia Camino. The functional system of the oasis city based on Bormida (2014).

(Mesa & de Rosa, 2001), which leads to lower specific consumption (kWh/m^2) in the central area of the city (Capital) (Mutani, Fontanive & Arboit, 2018). However, an increase in available sunny areas has been observed with the decrease in building density mainly on roofs (Mesa & de Rosa, 2001) (Figure 1). In this sense, solar energy offers great potential for active and passive space heating, domestic water heating, and photovoltaic generation.

-The "building separation" variable affects shading and airflows (Oke, 1988). After evaluating building separation, the values of the urban blocks of the MMA were significantly different in all departments, among which Luján stands out for having the highest average values. The building separation has an important impact on the effective sunshine on the northern facades. The presence of open spaces, combined with front and side setbacks, has a positive difference in the season with the highest energy requirement. In this way, Godoy Cruz and Capital stand out as the departments most compromised by their building separation, which could affect direct solar gain, ventilation, and daylighting (Figure 1).

-The NDVI describes the presence of vegetation in various strata. From the analysis of the results for all the blocks, which included the urban blocks by department, Luján de Cuyo registers the highest average value. The vegetation in summer reduces the surface temperature and allows keeping the radiation reflected towards the neighboring surfaces low, improving the habitability of public open spaces. Likewise, it increases air quality, mitigates runoff, provides habitat for biodiversity conservation, and favors community integration (Chen *et al*., 2020; Nowak & Greenfield, 2018).

In the case of Capital, the urban-building morphology is different due to the building height and the surface/volume ratio (SExp/Vol), in addition to the three urban-building variables mentioned above as PC1 and PC2. In this department, the construction technology, envelope use, and strategies differentiated by height are relevant (Ganem *et al*., 2021). When including tree cover, the "transmissivity", "magnitude" and "completeness" variables are significant. Urban public tree cover is capable of mitigating the negative impact of buildings, especially in the spring-summer seasons; while, in winter, deciduous species allow access to solar radiation (Figure 11).

This research will allow, in the future, to connect the findings of the Principal Component Analysis with the specific consumption (kWh/m^2) and total consumption (MWh) results (Mutani *et al*., 2018), to determine desirable intervention priorities and, in this way, implement energy efficiency and generation strategies, on different application scales. Another challenge that the work poses is to expand the study aimed at Capital incorporating tree cover data for all the blocks in the MMA. In this sense, the provincial government is working on an inventory of tree species that, from now on, will make it possible to update the analysis made and expand it to the remaining departments.

VII. CONCLUSIONS

Considering the number of variables that determine the urban-building form and its influence on energy consumption, this work has contributed by recognizing the urban-building variables representative of the oasis city, revealing their correlations, defining the Principal Components, and offering calculation equations for each of them.

It has been possible to contribute updated and quantitatively related data. Obtaining quantitative data on some variables is usually an inconvenience, so finding a representative combination of three or more variables (instead of thirteen) is another significant contribution when temporarily monitoring the urban-building morphology of the MMA for the future.

In summary, the results identify, in five of the six departments of the MMA, "building density", "building separation", and "NDVI". as essential variables of the first principal component. By including urban tree cover data in Capital, the results identify the "transmissivity", "magnitude" and "completion" variables together with those already recognized in the first three components. In conclusion, it can be stated that, in the face of climate change and urbanization, the MMA has the tools for adaptation and mitigation in its urban-building morphology, based on a territorial culture of controlled resource management, with which it has managed to accumulate valuable cultural capital that is reflected in the built landscape. All of this reflects a particular quality and, at the same time, a high fragility and vulnerability. Therefore, the high levels of complexity are not limited to morphological issues. In addition, the contribution of social science studies that address the issue of patrimonialization of the "oasis city" as a cultural-environmental common property of adaptation to the semi-desert climate and as a resource of local development and socio-cultural innovation, is required.

Finally, in a context of water scarcity, the main challenge lies in *how to revalue, preserve, and regenerate* the current "oasis city" model that allows access to the sun in the winter, access to night breezes in the summer, and a cool island during the middle of the day generated by the benefits of vegetation in the warm season. Some key aspects could be associated with the Principal Components of the urban-building morphology that will allow, in the future, proposing energy efficiency and generation strategies. Likewise, it is worth highlighting the need to link these environments with the native landscape through urban space *renaturalization* strategies.

The transdisciplinary work will allow focusing on urban-building morphologies to face the different cultural contexts, urban-building and landscape heritage, different opportunities, and limitations for progress towards energy-environmental sustainability.

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