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Vegetation cover and urban heat islands/oases distribution in Hermosillo City, Sonora

Cobertura vegetal y la distribución de islas de calor/oasis urbanos en Hermosillo, Sonora

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ABSTRACT
The case of an arid Northwest city of Mexico is studied with the general objective of assessing the influence of the percentage of vegetation cover (VC) in Land Surface Temperature (LST) and mapping its spatial distribution, through a geographic information system using remote sensing data. Results showed: 1) on average, 12% (min. 0 to max. 59%) of a city block is covered with vegetation, 38% of the blocks had % VC ≤ 10; 2) the LST regression model estimated temperatures range from 37 to 45°C, the main explanatory variable was % VC, increasing % VC in 10 is associated with cooling effect of 1.1 °C. The spatial heterogeneity in the distribution of LST can be interpreted as the human effect modifying the climate on a small scale; this creates internal diurnal oasis.

Keywords: 1. Urban heat island, 2. Urban oasis effect, 3. Vegetation, 4. Hermosillo, 5. Northwest Mexico.

RESUMEN
Se analiza el caso de Hermosillo, una ciudad del noroeste árido de México. El objetivo general es conocer la influencia del porcentaje de cobertura vegetal (CV) en la temperatura superficial del suelo (LST) y su distribución espacial a través de un sistema de información geográfica, utilizando datos de teledetección remota. En cuanto a los resultados, destaca en primer lugar que en promedio el porcentaje de CV en manzanas urbanas es de 12 por ciento (rango 0 a 59%), con un 38 por ciento de éstas con una CV ≤ 10 por ciento. En segundo lugar, que el modelo para estimar la LST detectó temperaturas promedio por manzana entre los 37 y 45°C, la principal variable explicativa fue el porcentaje de CV. Aumentar la CV en un 10 por ciento tendría el potencial de disminuir la LST en 1.1 °C. La heterogeneidad espacial en la distribución de la LST puede interpretarse como el efecto del ser humano modificando el clima a pequeña escala, esto crea un mosaico interno de oasis urbanos diurnos.

Palabras clave: 1. isla de calor urbana, 2. efecto oasis urbano, 3. vegetación, 4. Hermosillo, 5. Noroeste de México.

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INTRODUCTION

The global urban surface will expand over the following decade; this poses the challenge of managing sustainable cities. According to United Nations (UN) prospectives, by 2030, about 5,167.258 billion people will live in cities, which would mean to build a city for 1.5 million people every week. This is the outcome of a global tendency of urban growth, the population living in cities totaled about 54 percent in 2016 (United Nations, 2018). In Mexico, a decade ago such indicator was 78 percent (INEGI, 2010); following these projections for the same year, people living in urban environments will be about 123,198 million (United Nations, 2018).

The cities at the northwestern Mexican border, comprising not only those at the border line, but also the ones that are influenced by trans-border processes, which are integrated in industrial corridors, (Kopinak, 1997, Morales, 1999) for instance, the Phoenix - Tucson - Hermosillo - Guaymas corridor, have experienced a noticeable growth fostered by such processes over the last 40 years. Hermosillo, in Sonora, and Mexicali, in Baja California, have consolidated as the most populated arid cities in Mexico (INEGI, 2010); Tijuana, Baja California, with a template semiarid climate, and Mexicali, are the most important populations centers in the border zone in northwestern Mexico (Organización Panamericana de la Salud, 2012). On the Mexican side, the growth of the cities has been compact and more densely populated (Trubetskoy, 2016). This has posed significant challenges as regards urban planning, given that local governments have experienced difficulties maintaining and expanding basic services, infrastructure, and urban equipment (Acosta Enríquez, 2009). Among the most usual lacks, one finds public green areas and vegetation cover (Bernal Grijalva, Navarro Navarro and Moreno Vázquez, 2019; Ojeda Revah & Espejel, 2014; Ortega-Rosas, Enciso-Miranda, Macías-Duarte, Morales-Romero, & Villarruel-Sahagún, 2020; Peña Salmón, 2011).

The problem is that the basis of urbanization is eliminating natural environments with a view to creating urban ones. In this way, wildlife (flora and fauna) is removed, while soil, physiography, hydrology, and so on are disturbed, modified and adapted for the benefit of human beings. Public spaces and natural elements are introduced into the new cities via policies. As a whole, these are known as urban ecosystem; that is to say, these are the green or blue areas of a city (Bolund & Hunhammar, 1999). For its part, an urban forest is an important part of the biotic component of city ecosystems.

An Urban Ecosystem (UE) is a space that may be directly affected by public policy decisions. Politicians, legislators, leaders, and civil society influence on the definition of the proportion of the public space and construction designs, reforestation programs, etc., affecting the quantity, quality and distribution of the UE. They indirectly target the population that will receive the environmental benefits it produces; being important ones, the mitigation of heat and improving people's thermal comfort, which impact on the inhabitability of urban spaces. It is worth mentioning that the equity in the access to public

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spaces and green areas is a 2030 UN Sustainable Development Goal (United Nations, 2015) adopted by Mexico and set in the local agenda of states and municipalities (DOF, 2017; González Gómez, 2018).

Most of the local administration of the cities at the northern side of the border have acknowledged the formation of urban heat islands (UHI) (Chow, Brennan, & Brazel, 2011; Comrie, 2000; SDRUFC, 2020), where temperatures differ from the surrounding natural environment, have estimated the cover of their urban forests and set goals to increase it as a measure to mitigate the UHI effects. We can underscore the case of Phoenix, Arizona, which set the goal of increasing the cover of tree canopies from 10 to 25 percent by 2030 (Davey Resource Group, 2014).

On the Mexican side, important advance has been made in relation to generation of academic information (García-Cueto, Jáuregui Ostos, Toudert, & Tejeda-Martínez, 2007; Navarro-Estupiñán, Robles Morua, Díaz Caravantes, & Vivoni, 2020; Ojeda Revah & Espejel, 2014; Ortega-Rosas *et al*., 2020; Peña Salmón, 2011). However, not all the cities in the northwest have comprehensive studies on vegetation cover (VC) or data on the distribution of the urban forest cover, not even the intensity, distribution and characteristics of the UHI effects.

People in charge of setting public policies require accessible tools to estimate and monitor the sustainable management of UE. The use of remote sensing is an economically convenient alternative. This work contributes to the development and adaption of methodologies to process remote sensing data by means of the case study of the city of Hermosillo, located in the trans-border bioregion of the Sonoran Desert, in Mexico's arid northwest.

The overall objective of this research was to find out the influence of vegetation on Land Surface Temperature (LST). The specific objectives were: a) estimate the urban percentage of Total Average Vegetation Cover (%TAVC) at the level of urban block, using data from Google Earth (GE) and satellite Sentinel 2A; b) calculate LST from a Landsat 8 thermal sensor and analyze its spatial distribution in order to localize the internal presence of UHI or urban oases; and finally, c) relate LST and %VC.

THEORETICAL-CONCEPTUAL FRAMEWORK

The formation of an urban microclimate has been a well-known phenomenon for some time now. Its discovery is attributed to British meteorologist Sir Luke Howard (1772-1864), who studied thermal differences between London urban areas and the surrounding rural zones (Howard, 1833). According to Howard, "artificial" heat was produced by urban structures, population density and consumption of large amounts of fuels. Although the UHI term is formally attributed to Manley (1958), it had been already used in a number of publications (Landsberg, 1981).

At first, this phenomenon was studied through direct measurements of air temperatures using thermometers; usually, transversal thermal transects were made in the urban sprawl, starting and finishing in the rural environment. The data produced concentric isotherms, elongated to leeward from advection, with a descending gradient from the center toward the periphery. This thermal drift surrounded by lower temperatures, transcribed into a map, resembled an "island"; hence the name heat "island" (Oke, 1982, p. 3).

Generally speaking, the causes that produce the UHI effect are: a) the characteristics of many construction materials that are dark, which makes them absorb and store heat; b) these materials are impermeable and absorb little moisture, decreasing their capacity to transform heat into vapor (Gartland, 2008); c) a poor UE, i.e., little vegetation and few water bodies (Cai, He, Yang, & Deng, 2014; Gunawardena, Wells, & Kershaw, 2017; Qiu *et al.*, 2013); d) texture, design and architectural geometry (for example, "urban canyons") of the urban sprawl; and, c) heat generated by anthropogenic activities.

The arrival of the space age and thermal sensors on satellites enabled using a new tool to analyze this phenomenon. The literature states that Rao (1972) was the first to demonstrate that the UHI effect may be detected using data from thermal sensors (Gallo, Tarpley, McNab, & Karl, 1995); then, other studies able to detect this phenomenon ensued (Roth, Oke, & Emery, 1989). Despite the simplicity to obtain and analyze data from remote sensors, the thermal transect method is still widely resorted to (Georgakis & Santamouris, 2017; Smith, Webb, Levermore, Lindley, & Beswick, 2011).

An important difference between the two methodologies is that one measures air temperature, while satellites, LST; which García *et al*. (2007) called atmospheric and surface UHI effect, respectively. Since air is a poor heat conductor, LST is almost always higher than air temperature (Mildrexler, Zhao, & Running, 2011). There are ideal synoptic conditions for the UHI effect to express: a) anticyclonic conditions (high atmospheric pressure); b) clear sky; and, c) wind speed under five meters per second (Smith *et al.*, 2011). Likewise, cloudiness is an impediment for the use of satellite imagery.

Urban oasis effect

In cities in arid environments a phenomenon inverse to UHI takes place; it is known as urban oasis effect. The desert bare soil can reach very high temperatures, up to 70ºC in the Sonoran Desert, for instance (Nobel, 1984). Additionally, these cities tend to create oases supported on irrigation, which artificially keep a higher VC and a more diverse urban forest than the surrounding desert biomes (Fan *et al.*, 2017); plus, a strong tendency to use exotic vegetation (Navarro Navarro & Moreno Vázquez, 2016). Even the effect of "urban canyons" is the opposite, given that shadows reduce the incidence of solar radiation (Alobaydi, Bakarman, & Obeidat, 2016).

The cooling effect of vegetation comes from a greater evapotranspiration in the oasis as compared with the surrounding arid zones (Hao, Li, & Deng, 2016). In a city, an internal

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oasis may be an urban park (Declet-Barreto, Brazel, Martin, Chow, & Harlan, 2013), or a lake surrounded by vegetation, where energy dissipates through evaporation and evapotranspiration, producing cool-offs (Gunawardena *et al*., 2017).

However, this oasis effect is diurnal, for the cooling rate is faster in the rural environment that in the city. Grimmond, Oke, & Cleugh (1993) found out that the area of rural reference selected to compare with the urban center will determine the intensity of the UHI effect. The authors above discovered the oasis effect when they made a comparison with a rural arid zone, the city was cooler than the rural environment by 1-2ºC from 9 to 17 hrs. This effect was also reported for Teheran, Iran (Haashemi, Weng, Darvishi, & Alavipanah, 2016), and for Mexicali, Baja California (García *et al*., 2007).

Studies at regional and global level define UHI at city level (Matson, Mcclain, McGinnis, & Pritchard, 1978; Peng *et al*., 2012; Haashemi *et al*., 2016). On other occasions, the interest is to ascertain the spatial distribution of LST in the urban polygon in order to relate it with land use (García *et al*., 2007; Navarro-Estupiñán *et al*., 2020).

The literature (Chakraborti *et al*., 2019; García *et al*., 2007; Kim, Jun, Yeo, Kwon, & Hyun, 2019; Navarro-Estupiñán *et al*., 2020) suggests that there may be cold or warm anomalies depending on several factors. López Gómez, Fernández García and Arroyo Llera (1995) demonstrated that in the case of Madrid, Spain, the UHI effect is not uniform throughout the urban sprawl; there are secondary local minimums and maximums provoked by differences in volume and building density and open spaces as well (particularly parks).

Urban ecosystem and vegetation cover

It is important to conceptually clarify the relation between ecosystem, forest, and urban vegetation. In the first place, the urban environment is a mosaic of spaces with varying levels of biotic, abiotic, and anthropic elements that create a habitat for people and other living beings (mammals, birds, reptiles, fish, invertebrates, etc.) and this is what we call UE (Pickett *et al*., 1997; Endsley, 2018). As well, Endsley (2018) discusses that the urban area may be easily subdivided into two categories using remote sensors: impermeable surface and green surface. The latter encompasses urban vegetation, which Schmid (1975) defines as the spontaneous or grown (sowed, planted) vegetation within the city.

Secondly, VC refers to the percentage of soil surface covered with vegetation. VC can specifically measure foliage excluding open parts of plant canopy or the entire tree canopy, measuring the vertical projection of its outer perimeter; it may even include or not only live plants (BLM, 1999).

Some articles define urban forest as the set of vegetation contained in the city polygon (Sanders, 1984; Walker & Briggs, 2007). For example, Sanders (1984, p.15) mentioned that "the limit of an urban forest is established by a jurisdictional criterion and comprises all manner of vegetation within the urban area, regardless of its physical characteristics". These definitions contribute to confusion by equating "forest" and "urban vegetation".

Some other definitions emphasize the presence of trees as a necessary and sufficient condition for the existence of an urban forest, whereas the associated vegetation such as shrubs, herbaceous plants and grasses may be present or not. Miller, Hauer and Werner (2015) refer the urban forest as the sum of ligneous species and associated vegetation within and around dense living spaces, either in rural communities or large metropolitan zones. Benavides-Meza (1989, p. 967) points out: "the urban forest is composed of trees and associated vegetation that is found on sidewalks, avenues, medians, parks, gardens, cemeteries, right of ways and other spaces".

To conclude, the urban forest cover is associated to the concept of tree canopy cover, it is not synonym with total average vegetation cover percentage (%TAVC),[5] instead it is a subset of it. The clarification is relevant when indirect methods to ascertain %VC are utilized, as it is the case of aerial photography or Normalized Difference Vegetation Index (NDVI) (Tucker, 1979), which measures all the photosynthetically active tissue in a certain area.

CASE STUDY

According to data from the 2010 Population Census (INEGI, 2010), Hermosillo, capital city of the state of Sonora, was the most populated arid-climate city in Mexico ("BWh" according to Köppen-Geiger classification). It is located in northwestern Mexico (map 1) inside the Sonoran Desert bioregion (Shreve & Wiggins, 1964).

The state of Sonora has an aridity gradient that increases toward the West and North. To the West, elevation increases, and weather becomes semiarid (Felger, Johnson, & Wilson, 2001). The City of Hermosillo sits in the transition between semiarid and arid climates (INEGI, 1992); toward the coast, vegetation becomes scarce and desertic. The sort of vegetation that grows around Hermosillo is low shrubland, which may be described as a combination of around 27 sorts of middle-height trees, 17 belonging to Fabaceae, shrubs and some cacti (COTECOCA, 1986).

High temperatures are characteristic of Hermosillo; it is common to read news items about breaking a historic temperature record. For instance, on July 2nd, 2014, temperature reached 48.5º C, the item stated that Hermosillo was the hottest city in the world on such day (Sánchez Dórame, 2014). The analysis of data on maximum daily temperature for the period from 2000 to 2017 (CONAGUA, 2018) shows that there are 120 days (range 101-146) with a temperature higher than 100 °F (~38°C). This value may be compared with the city of Phoenix (1980-2010), which on average has 110 days with a temperature equal

[5] It is an average as it is always associated to a measuring geographic scale, for example, a city subdivided into polygons or pixels with a certain spatial resolution.

or higher than 100 ºF (National Weather Service, 2017). Navarro-Estupiñán *et al*. (2018) analyzed data from weather stations of *Comisión Nacional del Agua* [National Water Commission] in Sonora and their results made the overall increase in warm days and heat waves (+138%) evident.

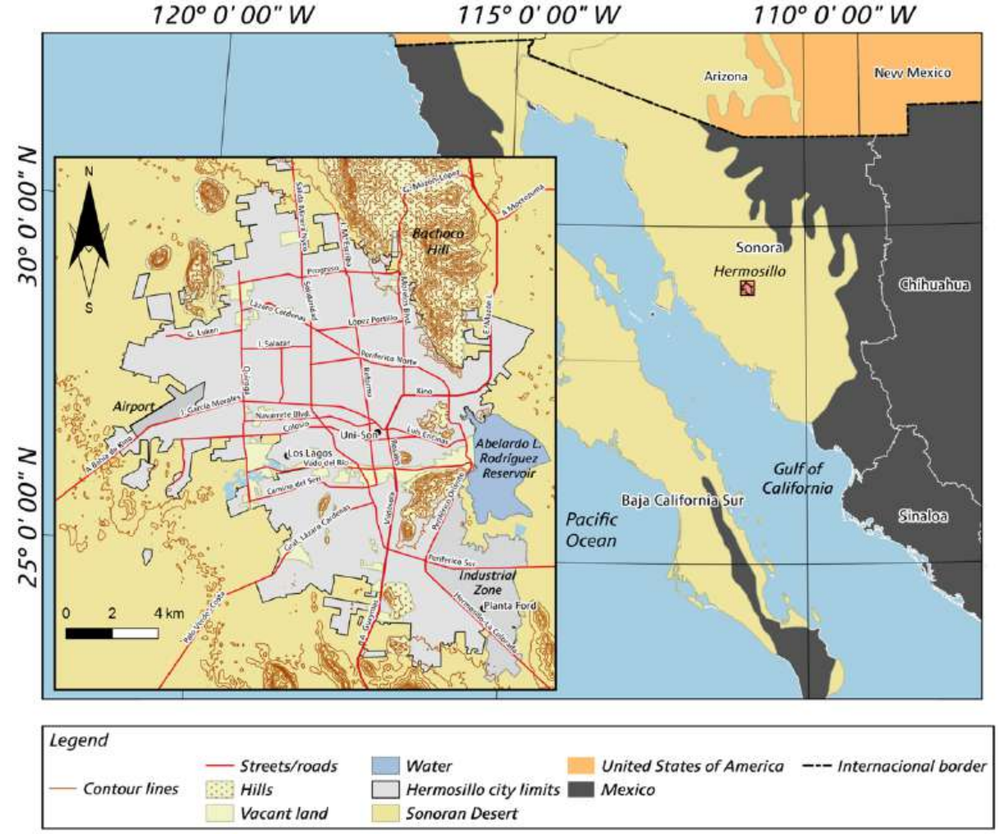
Besides warm summers, there is a shortage of water. In recent years, the image of the completely dry Abelardo L. Rodríguez dam, in the periphery of the city (map 1), is a piece of news that has received attention from local newspapers. According to Landsat satellite imagery for 2000-2018, the dam has completely dried up in 12 out of the last 19 years, remaining dry from April to late June; at present, the city has water 24 hours a day, though before 2013, when it began to be brought from the Yaqui River basin, threats of rationing were constant.

This is the context in which Hermosillo expanded between 2000 and 2017; it grew from 13,992 ha to 18,741 ha, while the population changed from 545,928 to 819,999 inhabitants[6] (INEGI, 2015). This expansion took agricultural land and desert shrubs used for grazing, transforming the natural ecosystem into an urban one (Lagarda Lagarda, Vázquez Landeros, & Noriega Nieblas, 2009).[7]

In Hermosillo's urban environment there are neither water bodies nor perennial streams that cross the city; map 1 shows the dam in blue and ephemeral lakes by the end of Sonora River ford, fed by rainfall (Boletín Oficial, 2014).[8] The streams that cross the city, far from being promoted as green riparian corridors, in most of the cases are turned into garbage dumps, recipients of runoffs and wastewater (Abril Fimbres, 2016; El Imparcial, 2014; López, 2018; Lozano, 2015). The city ended up deciding to channel such streams (Boletín Oficial, 2018a). This policy for rainfall discharge in the urban zone was recently changed by the coming into force of a technical norm that sets forth the characteristics and requirements to add green infrastructure in the municipality of Hermosillo (Boletín Oficial, 2018b).

[6] A 95-percent confidence interval; from 755,404 to 884,594.
[7] Observation of an aerial photograph taken in 1950.
[8] Interpretation of the map of use, reserves and projections for land.

Map 1. Regional location of Hermosillo



Source: own elaboration based on diverse digital cartography dowloaded from INEGI (2020), Portal de Geoinformación 2020 (CONABIO, 2020) and *Google Earth*.

Furthermore, little is it known about the vegetal component. In 2018, Barrera-Alarcón divided the city into 10 sectors, estimated a %TAVC of 20.99, a range from 7.09 to 50.43, using Landsat 8 data. Recently, the %VC of the urban forest was calculated, at the level of Basic Geostatistical Area (BGSA) by INEGI, as 6.4 percent by means of photo-interpreting high-resolution images (Ortega-Rosas *et al*., 2020). Navarro Navarro and Moreno Vázquez (2016) found that sidewalks (58%) and front yards (77%) had five or fewer trees per each hundred linear meters; that is to say, fewer than one tree per house in a yard or sidewalk. In 2016, Bernal Grijalva *et al*. (2019) calculated the surface of parks and gardens as 273 hectares, which meant 3.08 m^2 per inhabitant.

The heat waves in July 2018 around the world (BBC News, 2018) were also experienced in Mexico, particularly in Sonora, where *Fondo Nacional de Desastres Naturales* [National Fund for Natural Disasters] issued an emergency declaration due to a heat wave in 64 municipalities, including Hermosillo (DOF, 2018). These phenomena created a community concern about lack of greenness and trees in the city (Arellano, 2018).

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Strategy to reforest the city

Efforts to green Hermosillo's UE are usually set on the basis of number of planted or donated trees. Commonly, there is no follow-up for reforestations, for example, to assess the survival rate. Reforestation goals embellish the stats in the annual reports of the municipal government administrations. In table 1, the results of a document review of municipal reports from 1997 to 2018 are displayed. Although there is no single format to report these data annually, all the reports informed about reforestation activities and donations of trees. In total, there are about 720,309 trees planted over 22 years. Supposing they had grown and developed up to a canopy of 6 meters in diameter, they would account for a potential tree canopy cover of 11.31 percent, considering an urban sprawl of 18,000 ha.

Table 1. Report of trees planted or donated by municipal administrations of Hermosillo (source: own elaboration based on reviews of government reports)

Period	Planted or donated trees
1997-2000*	158 000
2000-2003*	47 321
2003-2006*	125 000
2006-2009*	194 333
2009-2012*	46 791
2012-2015*	44 273
2015-2018**	82 417
2018-2019***	22 174
Total	720 309

Sources: *Third governmental report by Valencia Juillerat (2000), Búrquez Valenzuela (2003), del Río Sánchez (2006), Gándara Camou (2009); Gándara Magaña (2012) and López Caballero (2015); **Three governmental reports by Acosta Gutiérrez (2016, 2017) and Fernández Muñoz Fernández (2018); and ***first report: López Cárdenas (2019).

Hermosillo's municipal plant nursery carries out a constant tree donation campaign, delivering from five to seven plants per individual; it houses a total of 50 exotic and native species and is able donate up to 10,000 plants a month (Inzunza, 2019). In addition to these donations, people can go to any of the 45 existing commercial plant nurseries (INEGI, 2019), which largely offer exotic species very colorful and ornamental.

The goal of planted trees should be accompanied by that of reaching a certain increase in the %TAVC or tree canopy cover of the city in the middle and long terms. The public or private space necessary to establish vegetation is a restriction. According to estimations by Navarro-Estupiñán *et al*. (2020), more than a half (60%) of Hermosillo's urban area is impermeable surface; distinguishable is the urban center (80%), heavily populated housing areas (75%), and 40.89 percent of the urban area is streets and roads; green areas account for only 1.87 percent of the total urban area.[9] In this way, priority zones for reforestation will have to be balanced (Ortega-Rosas *et al.*, 2020) with the spaces available for reforestation.

MATERIALS AND METHODS

Landsat 8 data

Satellite Landsat 8 is equipped with two sensors: OLI, Operational Land Imager, and TIRS, Thermal Infrared Sensor. Images were downloaded from the United States Geological Survey (USGS) website, they were taken on June 12, July 14, August 15, 2016, at 10:52 am local time and correspond to dates in the three months with the highest temperatures (CONAGUA, 2018). The days above met the ideal synoptic requirements suggested by Smith *et al*. (2011). The spectrum bands 4 (red) and 5 (near infrared) of OLI and 10 (thermal infrared) of TIRS were utilized.

Satellite imagery were cut to match with the limits of Hermosillo's polygon in 2017, which was created from the union of the urban BGSAs, the resulting polygon was updated using a GE image (March 27, 2017). A new raster was generated with the arithmetical mean of the three months; with OLI data, NDVI was estimated, while with TIRS data, LST.

Calculation of LST

In the first place, Fractional Vegetation Cover (FVC) was calculated according to Carlson and Ripley's (1997) equations. Secondly, following FVC, each pixel was conditionally assigned an emissivity value using the scale proposed by Skoković *et al*. (2014) and Sobrino *et al*. (2008). Finally, LST was calculated in Celsius using Avdan and Jovanovska's (2016, p. 3) procedure.

Estimation of VC from NDVI

The percentage of vegetation coverage was ascertained at the level of urban block; the entire procedure is described in figure 1. The total number of blocks in the city was 14,277 (INEGI, 2016), the final sampling frame was 12,180 blocks from which a simple random sample of 150 was taken.

The 150 blocks were photo-interpreted (Loelkes Jr., Howard Jr., Schwertz Jr., Lampert, & Miller, 1983) from a GE image dated March 27, 2017, classifying the area into two categories: a) impermeable surface (built space covered in concrete, asphalt, and other

[9] Adding vegetation to green areas would have a negligible effect on the city %TAVC.

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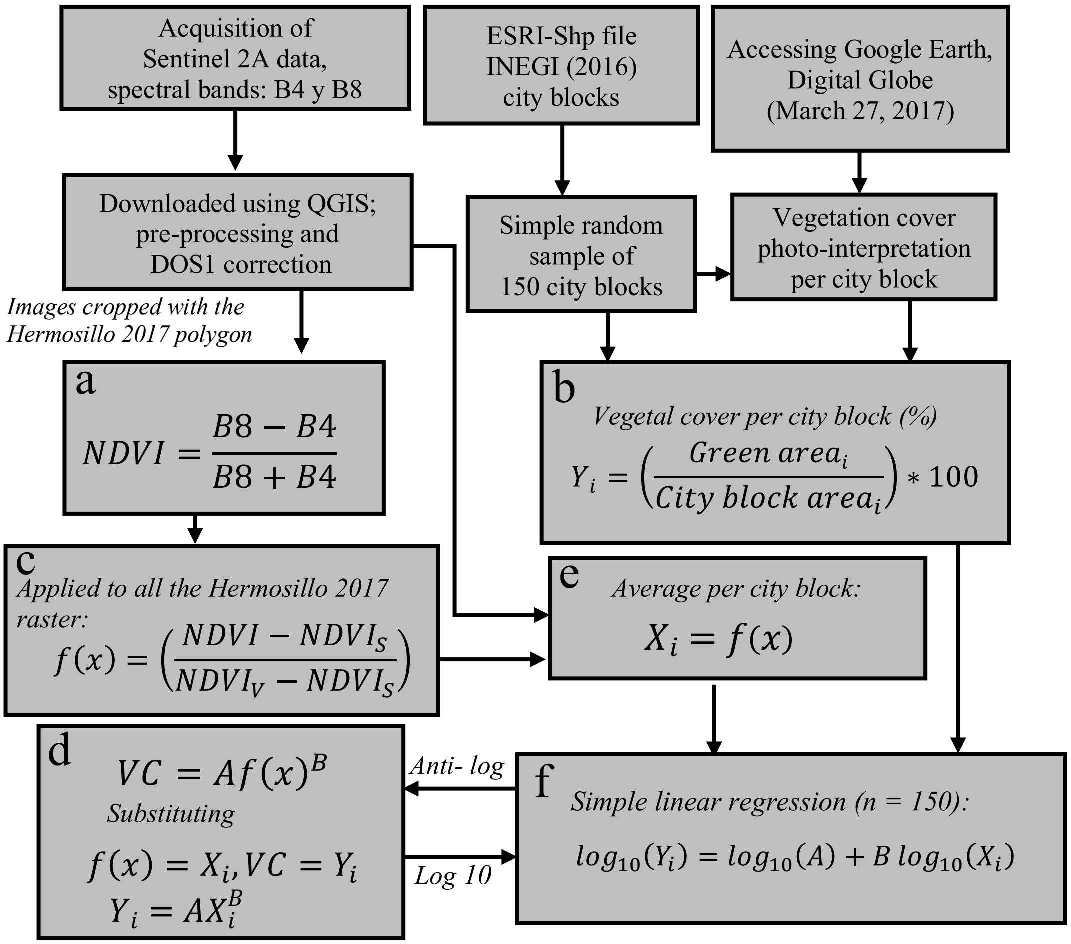
artificial elements); and, b) VC that comprises two elements: b1) urban forest (previously defined), and b2) herbaceous or grass strata.[10]

Figure 1. Flow chart to ascertain %VC from photo-interpreting and Carlson and Ripley's (1997) FVC



Source: own elaboration based on document reviews. Note: $NDVI_s$ = minimal NDVI value; $NDVI_V$ = maximum NDVI value; i = 1,2,3, …, 150 blocks.

With an image from Sentinel 2A (European Space Agency) (image date: 14/06/2017; 11:08 A.M. local time),[11] NDVI (Figure 1, inset "a"), Normalized Difference Water Index,

[10] Some comparison tests were carried out with other methods. For example: the estimates were consistent with those obtained from the free-access platform called I-Tree, created by scientists with the US Forest Service, which includes the tool I-Tree Canopy.
[11] VC was almost entirely composed of urban forest, which is an endurable and stable UE element; in this way, the one-year difference between the images for the calculation of LST and VC (2016 and 2017, respectively) was negligible.

NDWI, (McFeeters, 1996), Normalized Difference Build-up Index, NDBI, (Zha, Gao and Ni, 2003) were calculated.

Carlson and Ripley's (1997) exponential model was linearized (figure 1, "f") and a simple regression was run, where the dependent variable is VC from photo-interpretation (Yi) and the independent variable the mean F(x) per block (Xi) (Figure 1, "c" and "e"). Although this model may seem tautologic, it enables an empirical approximation to the values of A and B,[12] to relate the dimensionless values of NDVI to a tangible measure such as %VC.

Multivariate statistical model: LST and VC

A multivariate linear regression model was specified at the level of urban block to find out the influence of %VC on LST. The explanatory variables were: NDWI; NDBI; elevation (altitude), as suggested by Navarro-Estupiñán *et al*. (2020); houses per block; population by hectare. By means of Semi-automatic Classification Plugin (SCP) (Congedo, 2013) from QGIS (QGIS Development Team, 2017) the percentage of raster cells per block classified as reflective roofs, asphalt and bare soil.

RESULTS AND DISCUSSION

VC percentage

The relation between NDVI and %VC values, obtained from photo-interpretation, is presented in Equation 1. The model coefficients were statistically significant ($P < 0.001$) with a high explanatory power ($R^2 = 0.83$). Therefore, this study suggests that %VC per block can be estimated by means of NDVI using Carlson and Ripley's (1997) FVC formula.

Most of VC was tree canopy. Only in two out of the 150 photo-interpreted blocks was a small proportion of herbaceous or grass stratum detected. The month of March is part of the dry season in Hermosillo, greenness is explained by the trees, which comprise non-deciduous exotic species such as Benjamin fig (*Ficus benjamina*), black olive tree (*Bucida buceras*), bitter orange (*Citrus aurantium*), bastard cherry (*Ehretia tinifolia*), flamboyant (*Delonix regia*), indian laurel fig (*Ficus nítida*), plumeria (*Plumeria rubra*), among others which are the most abundant widely-distributed exotic arboreal species in Hermosillo (Navarro Navarro and Moreno Vázquez, 2016). A photointerpretation of a GE image between July and September would have showed a greater seasonal VC.

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[12] These are given values of B=2 and A=1, originally. In the regression, they are estimated as β_0 intercept and β_1 slope, respectively.

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The linear and exponential models specified in figure 1 are shown in equation 1.

Equation 1: Specified models

$$log_{10}(VC) = 0.16319 + 1.0208\, log_{10}(f(x))$$

$$VC = Af(x)^{B}$$

$$VC = 1.45609 * f(x)^{1.01208}$$

Note: for abbreviations, see figure 1.

According to this model, Hermosillo has a %TAVC of 11.93[13] (range from 0 to 59%), the distribution of frequencies indicates that 38 percent of the blocks has a %VC under 10 (see graph 1). This datum is comparable with the one found by Peña Salmón (2011, p. 242) for another arid city in northern Mexico, Mexicali, Baja California, the author estimated the TAVC of the urban sprawl as 13.88 percent. The result moves away from the calculation by Barrera Alarcón (2018), who uses large-extension polygons that encompass inter-urban rugged terrains and peripheral zones with native vegetation, considered growth reserves. Ortega-Rosas *et al*. (2020) calculated the mean percentage of tree canopy cover (urban forest) as 6.4 percent (CI 95% 0-39%). This result would be comparable with that of the present study, however they resorted to a larger geographic scale: BGSA. By and large, for desert American cities the mean urban forest cover was 10 percent; specifically, for instance, Tucson with 14 percent, and Ciudad Juarez with 4 percent (Nowak *et al*., 1996). More recent studies on cities at the arid and semiarid border strip include San Diego, California, with 13 percent (SDRUFC, 2020), and Yuma, Arizona, with 3.5 percent (City of Yuma, 2019). Table 2 shows a comparative summary of the results of this work with those from other studies.

[13] Confidence interval (CI) at 95% 11.83-12.04%.

Table 2. Comparison of results of %TAVC with other studies

City	Reference	Sort of %VC	Value (%)	Observations
Hermosillo, Sonora	This work	TAVC	11.93	See methodology
Hermosillo, Sonora	Barrera Alarcón (2018)	TAVC	20.9	NDVI from Landsat 8, 30-m resolution; with very large polygons that encompass inter-urban rugged terrains and peripheral areas with native vegetation.
Hermosillo, Sonora	Ortega-Rosas *et al.* (2020)	Urban forest	6.4	High-resolution ortho-photo-interpretation. 10-percent sampling of each BGSA area.
Mexicali, Baja California	Peña Salmón (2011)	TAVC	13.9	NDVI from Quickbird, 2.6-m resolution. Public and private zones within the urban sprawl.
Ciudad Juarez, Chihuahua	Nowak *et al.* (1996)	Urban forest	4.0	Sampling of census areas. Method not specified.
Yuma, Arizona, US	City of Yuma (2019)	Urban forest	3.5	Aerial photograph. Method not specified.
San Diego, California, US	SDRUFC (2020)	Urban forest	13.0	LIDAR from flights and high-resolution imagery.

Source: own elaboration.

Furthermore, 593 polygons corresponding to urban parks managed by the Directorate of Parks and Gardens of the municipality of Hermosillo were used, estimating a mean VC of 20.92 percent (see graph 2). Bernal Grijalva *et al.* (2019) found a value of 27 percent for a sample of 112 parks. Map 2 summarizes the results; dark green indicates areas with a higher %VC.

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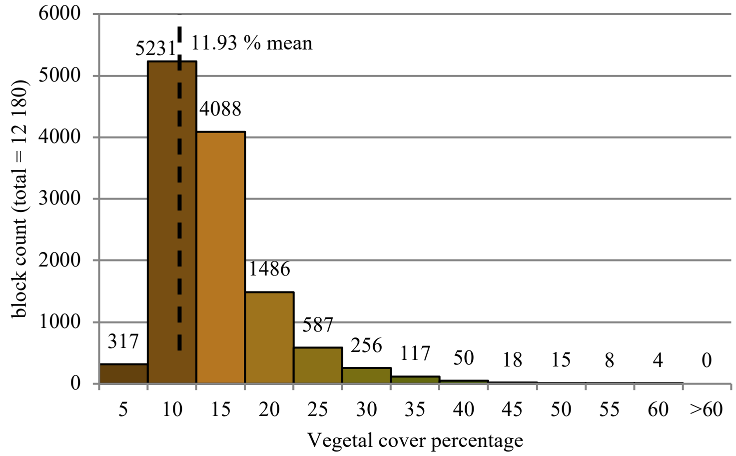
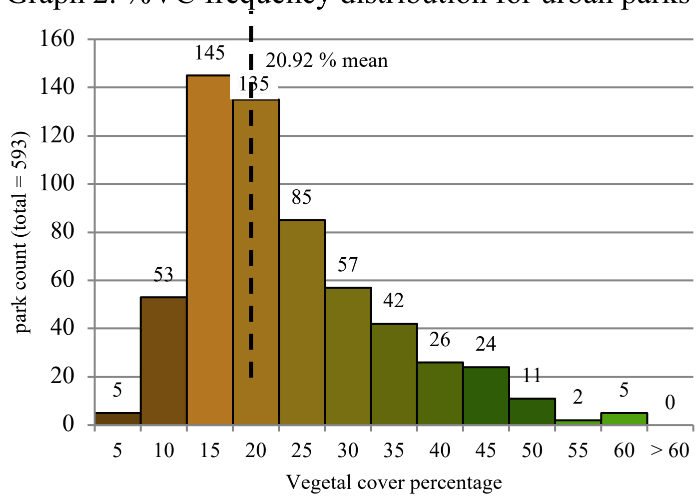
Graph 1. %VC frequency distribution by urban blocks



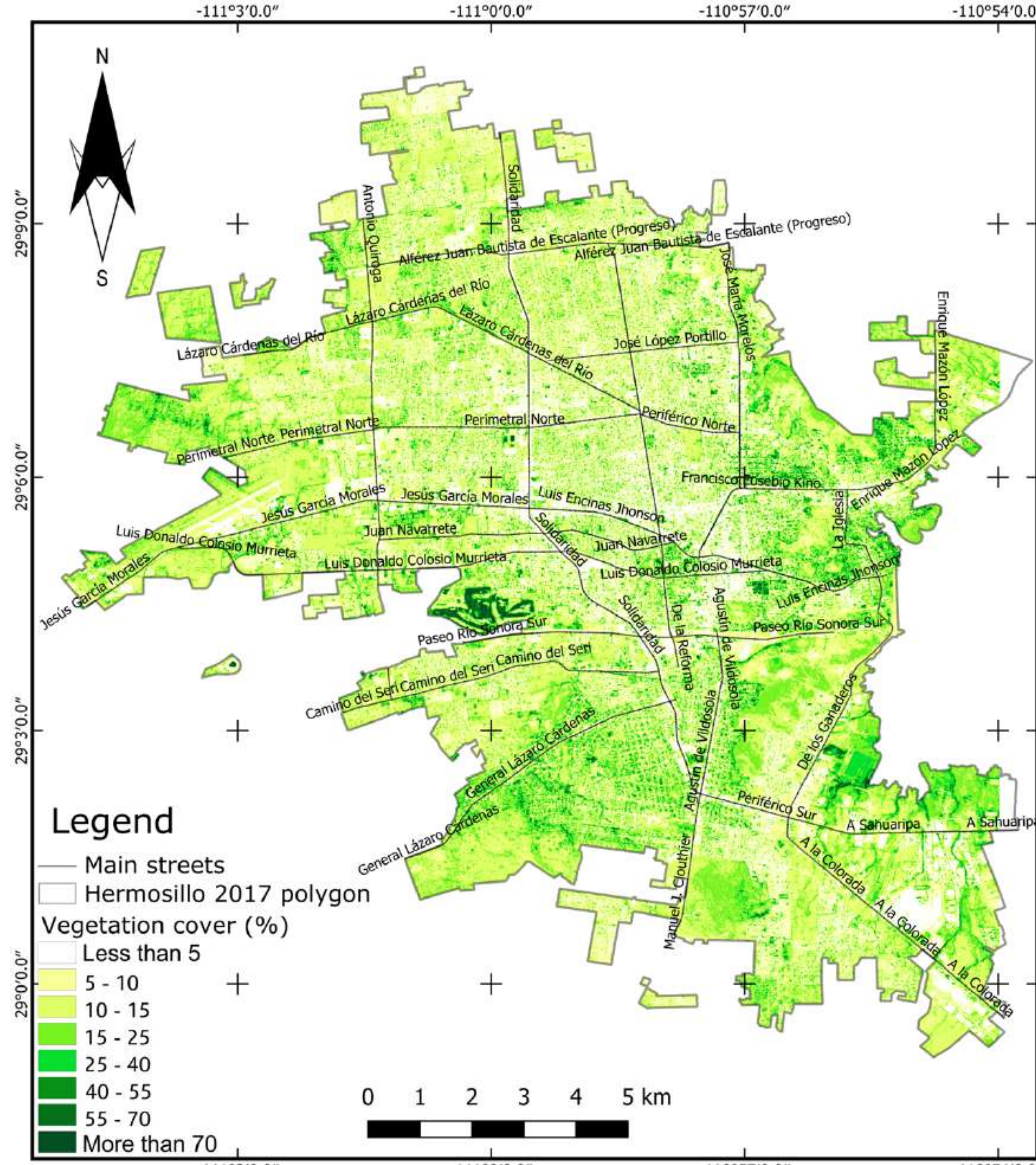
Source: own elaboration based on data from Sentinel 2A, GE 2017 and INEGI (2016).

Graph 2. %VC frequency distribution for urban parks



Source: own elaboration based on data from Sentinel 2A, GE 2017 and INEGI (2016)

Map 2. %VC distribution according to Equation 1



Source: own elaboration with data from Sentinel 2A and Google Earth 2017.

Temperature distribution

The mean LST range per block was 37.35 - 45.44° C. Map 3 summarizes the results, red indicates areas with high temperatures and blue, low values; visually, there is a heterogeneous spatial distribution of this variable.

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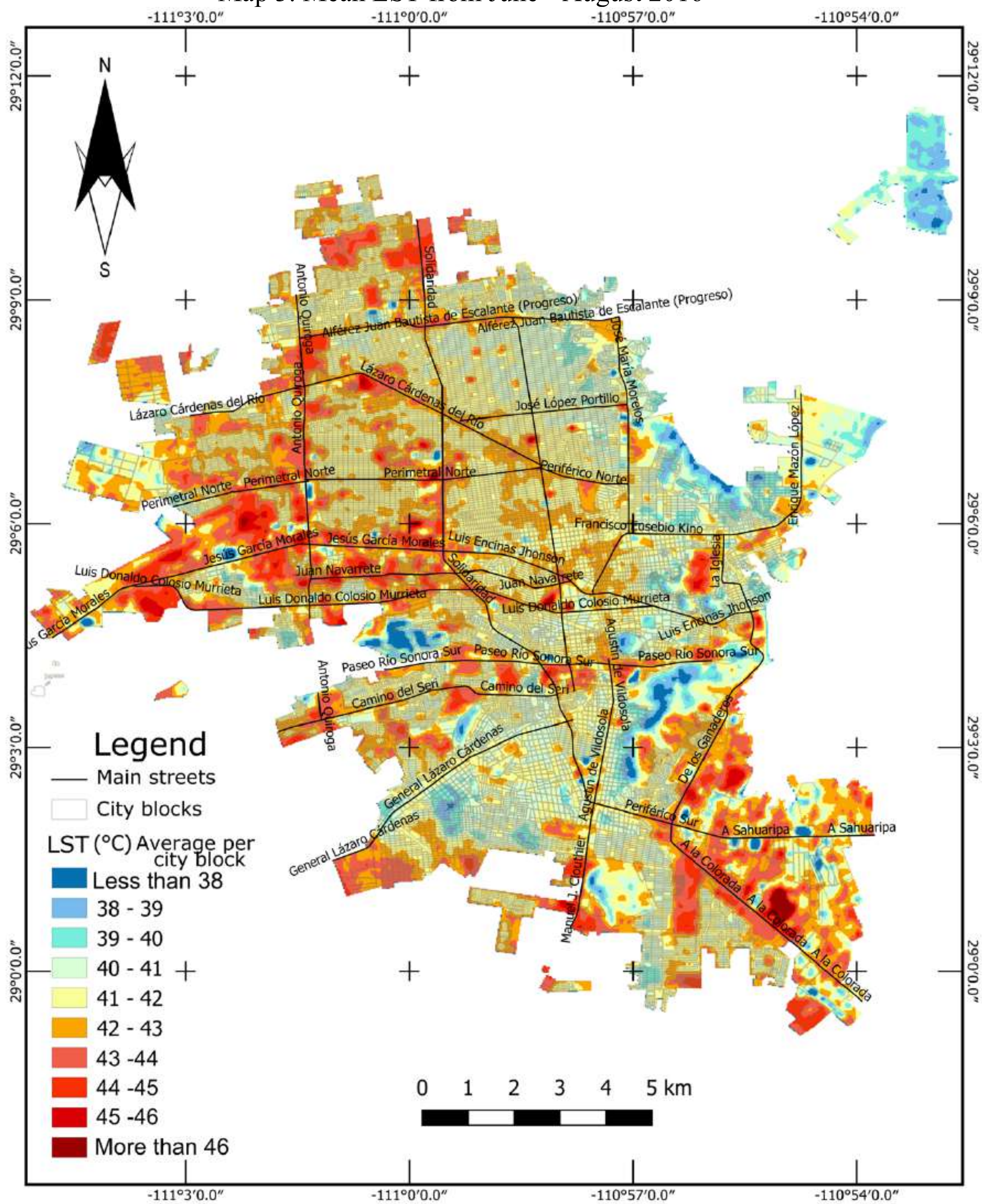
The visual supervision of the LST map suggests the formation of warm or fresh clusters. The global Moran index (Moran, 1950) was calculated as 0.96 (P < 0.01), verifying the existence of a positive spatial autocorrelation. This indicates that pixels with positive (or negative) deviations from the mean are adjacent.

Map 3. Mean LST from June - August 2016



Source: own elaboration with data from Landsat 8.

LST map was visually contrasted with similar maps produced by Mercado Maldonado and Marincic Lovriha (2017), Barrera Alarcón (2018) and Navarro-Estupiñán *et al*. (2020), with important coincidences in many warm and fresh clusters. Additionally, the research results reaffirm that Hermosillo's UHI does not follow the typical pattern of concentric isotherms with a descending gradient from the center toward the periphery, but a mosaic of warm and fresh areas; this concurs with findings by García-Cueto *et al*. (2007) for Mexicali.

Figure 2 shows information on these clusters obtained via the local Moran index (Anselin, 1995). Cold or warm points were taken from the clusters with statistically significant high or low values ($P <= 0.05$). Later on, contour lines, isolines, were produced utilizing local Moran index values; these lines served as a guide to detect concentration points, from which the central pixel was taken. In total, 304 urban oases and 326 UHI were identified, with a mean LST of 38.9°C and 44.2ºC, respectively. The difference between these clusters was statistically significant ($P < 0.01$). For Hermosillo, in warm months from June - August, 38ºC may be considered an urban oasis on this temperature measurement scale.

With a random sample of 32 UHI and 32 urban oases, the sort of cover and use of soil in each point was photo-interpreted. It was possible to verify that vacant land with bare soil, asphalt and sports parks with synthetic grass consistently appear as UHI. The high LST of bare soil in desert zones is a common finding in other studies (Bokaie, Zarkesh, Arasteh, & Hosseini, 2016; García-Cueto *et al*., 2007; Ibrahim & Rasul, 2017). The heat source with the highest temperature in the city is in a 280-cell raster cluster with a mean LST of 52.3°C (range 50.06-54.16°C) in the industrial area, where the stamping and assembly Ford factory is.

On the other hand, areas with abundant vegetation: medians in boulevards, parks with no synthetic grass, margins of streams and rugged terrains, areas near the urban periphery (figure 2) largely appear as urban oases. Consistently, roofs (about 30) with high albedo (white in color) that become cold clusters are observed, which are as relevant as urban parks with high VC. The effect of these roofs is very significant (Costanzo, Evola & Marletta, 2016); this way, they appear as urban oases with no VC.

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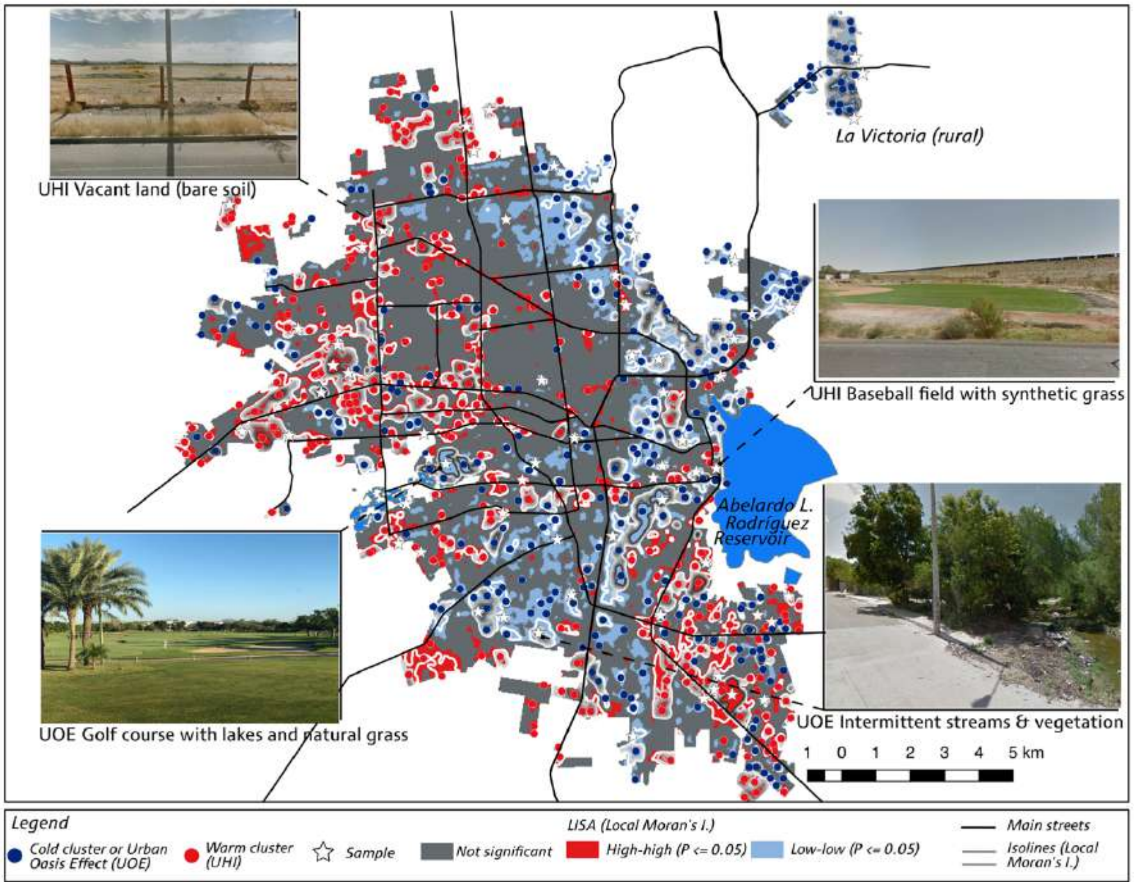
Figure 2. Spatial distribution of the oases (cold clusters) and urban heat islands (warm clusters) estimated with the local Moran index



Source: own elaboration with data from Landsat 8 and *Google Earth*.

Temperature and VC

Finally, LST was related to %VC. The variables were sequentially included with a view to comparing the full model (model 9) with a set of nested models (table 3). The parsimony principle (Occam's razor) stipulates that the simplest model is the one to choose.

With these results, we conclude that model 8 is the one that best fits the data ($R^2 = 0.33$). At urban-block scale, the model found a statistically significant negative correlation between LST and %VC. According to model 8, an increase in VC from 0 to 50 percent would have an effect of 5.7°C on the reduction of LST, as it would be the case of reforesting a park where, as deduced from graph 2, there is a large opportunity area to turn parks into urban oases. For the city of Hermosillo, Ortega-Rosas *et al*. (2020) suggested that increasing the urban forest cover in 10 percent would have an effect on the reduction of the daily mean maximum temperature of 0.11°C (CI at 95% 0.05-0.14), and a diminution of 0.4°C (CI at 95% 0.21-0.49) of the mean air temperature.

Table 3. Results of the estimations of the nested multivariate linear regression models

Variable/ Indicator	Mean and range◇	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9
Intercept	--	42.0300 ***	44.0800 ***	43.2900***	43.4500* **	43.6100 ***	42.8200 ***	42.7800 ***	42.8900***	42.8900 ***
%VC	12.05 (0-59.44)	-0.0511 ***	-0.0516 ***	-0.1034 ***	-0.0864 ***	-0.0777 ***	-0.1059 ***	-0.1054 ***	-0.1125***	-0.1135***
Elevation (meters)	219 (171-351)	--	-0.0093 ***	-0.0086 ***	-0.0090 ***	-0.0092 ***	-0.0080***	-0.0080 ***	-0.0074 ***	-0.0074 ***
NDWI (x 100)	-15.93 (-39.46-0)	--	--	-0.0798 ***	-0.0619 ***	-0.0489 ***	-0.0989 ***	-0.0970 ***	-0.0972 ***	-0.0980 ***
NDBI (x 100)	0.03 (-20.65-21.75)	--	--	--	0.0397 ***	0.0511 ***	0.0365 ***	0.0336 ***	0.0211***	0.0205 ***
Reflective roofs (%)	0.87 (0-58.79)	--	--	--	--	-0.0217 ***	-0.0163 ***	-0.0155 ***	-0.0163 ***	-0.0162 ***
Asphalt (%)	2.23 (0-100)	--	--	--	--	--	0.0342 ***	0.0348 ***	0.0299 ***	0.0297 ***
Bare soil (%)	38.19 (0-100)	--	--	--	--	--	--	0.0012 ***	0.0016 ***	0.0016 ***
Population/hectare	102 (0-383)	--	--	--	--	--	--	--	-0.0015 ***	-0.0012 ***
Houses/hectare	34 (0-80)	--	--	--	--	--	--	--	--	-0.0009
Residual DF	--	11 504	11 503	11 502	11 501	11 500	11 409	11 408	11 407	11 406
R^2	--	0.1287	0.2175	0.2490	0.2679	0.2747	0.3233	0.3239	0.3340	0.3341
R^2 Adjusted	--	0.1287	0.2174	0.2488	0.2677	0.2744	0.3230	0.3235	0.3335	0.3336
AIC	--	27 314.7	26 080.3	25 609.9	25 317.7	25 212.5	24 416.3	24 408.4	24 237.7	24 238.1
SCR	--	7 231	6 495	6 233	6 076	6 020	5 616	5 611	5 528	5 527
▵ SCR	--	--	737 ***	261 ***	157 ***	56 ***	403 ***	5 **	84 ***	1

Note: * *p<0.05* ** *p<0.01* *** *p<0.001*; DF: degree of freedom.; ▵ SCR: change in residual sum of squares. Observations: 11 506. ◇ Mean values per block. By raster cell at polygon scale, ranges are different: %VC (0-91), NDWI (-71.62-58.53), NDBI (-55.06-91.12), LST (28.97-54.20). Houses/hectare was restricted to 80 (95% of blocks).

Source: own elaboration with data from Landsat 8, *Google Earth*, Sentinel 2A and INEGI (2010, 2016).

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As regards control variables, not all the signs of the coefficients corresponded to those expected. Housing and population density variables were negative with a very reduced impact, it was expected that densely populated zones had a larger built surface (Navarro-Estupiñán *et al*., 2020) as well as a higher LST. The signs of NDWI and NDBI were as expected, and their inclusion doubled the explanatory power of the reduced model. The relative amounts of asphalt, bare soil and reflective roofs per block had coefficients as expected, though with very low magnitudes.

The absence of natural or artificial streams and water bodies as components of Hermosillo's urban ecosystem components was noticed with NDWI. It fluctuated from -0.716 to 0.585, only 0.005 percent of all the cells recorded a value over 0.1, threshold from which the presence of water is detected; such cells were left out of the grid of urban blocks. High negative values (<-0.38) were related to green areas, whereas less negative values (∼-0.25-0.01) with bare soil or impermeable cover; which turned into a strong negative correlation between %VC and NDWI (-0.83, $P < 0.05$).

The results suggest that control variables related to soil uses are needed so that a better model specification is expected. For example, there were many mixed-use blocks that were sparsely populated and many undeveloped plots with bare soil, which were identified as warm clusters; moreover, there were also unpopulated blocks with green areas or sporting land use and abundant VC, and blocks with enclosed shopping centers with highly reflective roofs, which were considered cold clusters. However, the results of Navarro-Estupiñan *et al*. (2020), which relate LST and soil uses, show little variance between them. In the present study, only 2.5 percent of raster cells had superior (inferior) values to two standard deviations for LST.

CONCLUSIONS

The use of remote sensing data offers a robust and sufficient accurate option to monitor UE, in particular, its green component. Data are constantly improving in accuracy and resolution. What is most important, there is a global policy of governments that sponsor spatial programs to make them available to the public for free.

Water bodies and courses as well as UE flora have the potential to mitigate the UHI effect, improving the inhabitants' thermal comfort. However, "green" or "blue" areas in Hermosillo are scarce. The "blue" component is minimal and is represented by non-induced spaces (neither created nor designed) along the course and shores of the Sonora River ford such as La Sauceda wetland, the only water body for recreational use open to the public.

Furthermore, the results estimated a %TAVC for the city of Hermosillo of 11.93% (range 0-59%); according to the model, 38 percent of the urban blocks have a %VC equal or smaller than 10, this is, 90 percent of them has impermeable surface or bare soil. VC is largely composed of tree canopy. In dry season, the greenness of the city is explained by trees and shrubs since the herbaceous layer is virtually inexistent.

The following objective was the estimation of LST. The obtained results were in the range from 37.35 to 45.4 °C average LST per urban block. A statistically significant negative relationship between LST and the proportion of VC per block was found. The model suggested that an increment in 10 percent of VC would reduce LST in about 1.1ºC.

LST distribution in the urban polygon did not show the typical pattern with a warmer central nucleus and a descending gradient toward the urban periphery. It resembles a mosaic of warm or cold clusters. The spatial heterogeneity in the distribution of the LST variable may be interpreted as the effect of human beings' modifying the weather at small scale, which creates oasis effects or diurnal cold clusters, a result of the presence or more VC.

Considering that UE and its green component are spaces designed by human beings, the implications of these results in public policies suggest promoting the sustainable densification of the urban forest –taking the context of water scarcity into context–, under the premise of accomplishing an urban-scale homogenous spatial distribution that provides universal access for the environmental services vegetation offers, for example, urban oases. Reforestation goals must be carried out with a view to increasing %TAVC, not only the number of planted trees.

The present analysis produces results at a resolution sufficient to be able to recommend mitigation actions at local level; this methodology is useful for governments and research centers to observe and monitor the urban environment and its benefits for people's wellbeing.

Translation: Luis Cejudo-Espinosa

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