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LA VEGETACIÓN COMO AMORTIGUADOR DE TEMPERATURAS EXTREMAS

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THE VEGETATION AS EXTREME TEMPERATURE REGULATOR

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ABSTRACT

The increase in atmospheric temperature affects the economy, health and well-being of the urban population. In order to mitigate these adverse effects, various alternatives have been proposed. Urban trees stand out as one of the most efficient by providing additional services such as air purifier, increasing the value of the land and beautifying the landscape. This work reports and analyzes the land surface temperature distribution in the city of Tuxtla Gutiérrez (TGZ), in the state of Chiapas, Mexico, using thermal remote sensing techniques. Besides, the performance of vegetation as a temperature buffer in one of the neighborhoods of the city identified as a *hot spot* was evaluated. Finally, savings in energy consumption and cost in 51 houses in the Monterreal neighborhood, due to the shade they receive from the tree, were estimated. The results show that land use change and tree coverage in the city of TGZ significantly affects the thermal distribution. The change of tree cover into asphalt road, bare soil or bare agriculture soil (BAS) cover caused a land surface temperature increased (LST) of 1 °C to 3 °C. Tree shade reduced the surface sidewalk and house exterior wall temperature by 26.5 °C and 6 °C, respectively. Tree shade also reduced air temperature next to an exterior wall by 3.43 to 3.99 °C and reduced temperature next to an interior wall by 0.96 to 1.25 °C. Furthermore, tree shade promoted stable air temperature environments with a thermal oscillation of less than 2 °C in the hottest hours the day. The 71% of the dwellings surveyed combine the use of a fan with air conditioning (AC). Consumption of electricity *per capita* (CE_{pc}) was reduced by 32% when the houses received tree shade, generating an average saving of 43% in the annual cost.A recommendation to reduced house exterior and interior house temperature is to plant trees with globose crown shape at the east side house and to paint exterior walls with white or clear colors. These actions will help to mitigate the maximum thermal hours. In general, the thermal mitigation effect is perceived when trees are 2.5 m tall and are located at 5 m of distance from houses.

Key words: Energy consumption, Land surface temperate, Urban tree, Urban heat island.

LA VEGETACIÓN COMO AMORTIGUADOR DE TEMPERATURAS EXTREMAS

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RESUMEN

El aumento de la temperatura atmosférica afecta la economía, la salud y el bienestar de la población urbana. Para mitigar estos efectos adversos se han propuesto diversas alternativas. La vegetación arbórea urbana se destaca como una de las más eficientes al brindar servicios adicionales como purificador de aire, aumentar la plusvalía de la tierra y embellecer el paisaje. Este trabajo reporta y analiza la distribución de la temperatura de la superficie terrestre en la ciudad de Tuxtla Gutiérrez (TGZ), en el estado de Chiapas, México, utilizando técnicas de teledetección térmica. Posteriormente, se evaluó el desempeño del arbolado como amortiguador de temperatura en una de las colonias de la ciudad identificada como *hot spot*. Finalmente, se estimó el ahorro en el consumo y costo de energía en 51 viviendas de la colonia Monterreal, relacionado con la sombra que reciben del árbol. Los resultados muestran que el cambio de uso de suelo y la cobertura arbórea en la ciudad de TGZ afecta significativamente la distribución térmica. El cambio de uso de suelo de árbol a camino asfaltado, suelo desnudo o suelo agrícola desnudo (SAD) provocó un aumento de la temperatura de superficie (TS) de 1 °C a 3 °C. Se descubrió que la sombra de los árboles redujo la temperatura de superficie de la acera y de la pared exterior de la casa en 26.5 °C y 6 °C, respectivamente. La sombra de los árboles también redujo la temperatura del aire junto a una pared exterior entre 3.43 y 3.99 °C y la temperatura junto a una pared interior entre 0.96 y 1.25 °C. Además, la sombra de los árboles promovió ambientes estables de temperatura del aire con una oscilación térmica de menor a 2 °C durante las horas más calurosas del día. El 71% de las viviendas encuestadas combinan el uso de ventilador con aire acondicionado (AC). El consumo de electricidad *per capita* (CE_{pc}) se redujo en un 32% cuando la vivienda recibió sombra de árboles, generando un ahorro promedio del 43% en el costo anual. Una recomendación para reducir la temperatura exterior e interior de la casa es plantar árboles con forma de copa globosa al Este de la casa y pintar las paredes exteriores con colores blancos o claros. Esto ayudará a mitigar la temperatura durante las horas de máximas térmicas. En general, el efecto de mitigación térmica es apreciable cuando los árboles miden 2.5 m de altura y se ubican a 5 m de distancia de las viviendas.

Palabras clave: Árbol, Consumo de energía, Isla de Calor Urbana, Temperatura de superficie.

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DEDICATION

This work is devoted to:

My sons. Only they know what concluding this thesis has meant for our family. I appreciate your childlike patience, encouragement and faith in me. Solo ellos saben lo que para nuestra familia ha significado concluir esta tesis. Agradezco su paciencia infantil, sus ánimos y fe en mí.

My parents. In gratitude for all your support and effort. It is a shared achievement. En agradecimiento por todo su apoyo y esfuerzo. Es un logro compartido.

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INTRODUCTION

Beginning in the 18th century, the growth and establishment of cities was driven by the Industrial Revolution (Robledo et al., 2016). This period was the one with the greatest transformation of the environment caused by man (Suárez & Molina, 2014). The effects on health and ecosystems generated by sprawl were noticed at the beginning of the 19th century; for example, in the city of London, the phenomenon known as Urban Heat Island (UHI) was described as the increase in temperature within the urbanization compared to surrounding rural áreas (Howard, 1988).

Since urban growth then, the temperature increased has been constant and some consequences in cities are: greater demand of energy for cooling buildings (Coello, 2015; Salamanca et al., 2014) and water (Yool et al., 2009), which also increases the cost of living; the raised of harmful fauna such as vectors of tropical diseases affecting temperate cities where they were not common, and the increase in the concentration of gases and volatile particles in urban envieronments (Han et al., 2020; Díaz-Nigenda et al., 2018).

The UHI phenomenon received little attention until the 20th century, when the consequences in the environment began to be obvious throughout the world (IPCC, 1992). Since 1988, the global warming effects and mitigation strategies had been systematically studied by the Intergovernmental Panel of Experts on Climate Change (CC) with a global approach. However, on the local scale, it is still necessary to generate information for appropriate mitigation strategies in each region and country.

In Mexico, the industrialization and urbanization in comparison with Europe was late and polarized to temperate zones of the center and north of the country (Reyes & López, 2011; Unikel, 1968). However, urban growth has been constant to the point that the urban population represents 79% of all inhabitants (INEGI,

2022) whose distribution is concentrated in tropical areas of the country (Reyes & López, 2011).

The present work seeks to generate information regarding the UHI phenomenon in the city of Tuxtla Gutiérrez, Chiapas. Therefore, the relationship between UHI with land use and tree crown coverage through thermal remote sensing is studied. The distribution and intensity of *hot spots* throughout the city is also identified.

Then, the tree shade mitigating effect on extreme house temperatures was measured. Direct measurements were made with thermometers installed in houses located at the Monterreal neighborhood, previously identified as a *hot spot* in the city of Tuxtla Gutiérrez. Finally, the relationship between temperature and energy consumption associated cost in houses in the Monterreal neighborhood was studied. The difference in energy consumption is established between those houses with the influence of tree shade and those that receive direct sunlight.

Problem statement

The state of Chiapas is socially, economically, and environmentally contrasting. It has an exceptional environmental richness (CONABIO, 2013), but also a great degree of socioeconomic marginalization (CONAPO, 2010) with an extremely contrasting biophysical conditions such as abrupt topography, tropical climate, karstic geology and the occurrence of extreme hydrometeorological events.

Tuxtla Gutiérrez is the largest city in Chiapas state and ranks 30th out of the 117 most populated cities in Mexico. There is great pressure on forest spaces due to the demand for residential use and urban infrastructure (Silva et al., 2015), ignoring the services they provide as mitigators of extreme temperatures (Nowak et al., 2006).

The effects of rapid urbanization have already been perceived by the city's people with extreme hight temperatures recorded during the hot season from April to June (Zavaleta-Palacios et al., 2020). This seasonal behavior of public health costs millions of Mexican pesos, but it also has an economical implication for the population. During the hot season there is an increase on the demand of electrical energy for house cooling (McNeil et al., 2018; Akbari et al., 1997).

In general, a tree performs several environmental services simultaneously, but one of the least explored is as a temperature regulator. For this reason, in the present work, we seek to demonstrate the added value that trees have as cooling system in the microclimate of the city of Tuxtla Gutiérrez mitigating the intensity of the UHI, as well as to determine the cost/savings that trees mean as a house thermal regulator.

Research questions

This work is defined by three research questions, which are addressed in each chapter:

Chapter 1. The Urban Heat Island (UHI) phenomenon and factors have not been studied in the city of Tuxtla Gutiérrez. Being the city with the largest population and the center of the economical development in the state of Chiapas, the negative effects of the UHI have also socioeconomic implications. Changes in land use and vegetation cover have a significant influence on the UHI phenomenon, in different cities around the world; however, the relationship has not been investigated in the city of Tuxtla Gutiérrez. Question 1: How does the change in land use and vegetation cover influence the temperature of the city of Tuxtla Gutiérrez? Question 2: Where are located the hottest areas of the city?

Chapter 2. One of the most used UHI mitigation strategies in the world is the increase of tree cover. Green area benefits are not limited to lowering the temperature, but also improve the appearance of the city and the quality of the air, among other benefits. Therefore, question 1: In the city of Tuxtla Gutiérrez, to what extent does urban tree shade help to reduce the temperature of sidewalk and houses? In particular one of the hottest areas identified in the city; the Monterreal neighborhood. Question 2: What factors increase or decrease the temperature mitigating effect of trees?

Chapter 3. Studies of economic urban tree benefits are scarce; mainly due to the complication of obtaining people information that helps to quantify and value the ecosystem service provided by the tree. Question 1: Is there a difference in electricity consumption between uses that are shaded by a tree and those that are not? Question 2: Does the difference in electricity consumption, between households that are shaded by a tree and those that are not, implies a saving in the electricity bill?

Objectives

General

Evaluate the effect of trees as a mitigating factor of extreme temperatures in the city of Tuxtla Gutiérrez, Chiapas, Mexico.

Specific

a) Identify the areas with the highest surface temperature, called *hot spots*, within the city of Tuxtla Gutiérrez.
b) Measure the effect of shade generated by trees in mitigating temperature.
c) Estimate the savings generated by the effect of the canopy shade in the consumption of electrical energy due to the use of air conditioning equipment and therefore electricity.

Hypotesis

Vegetation does not contribute to mitigating the increase in temperature in areas considered as heat islands.

Research overall methodology

The methodology for the three objectives of the work is schematically represented in Figure 1.

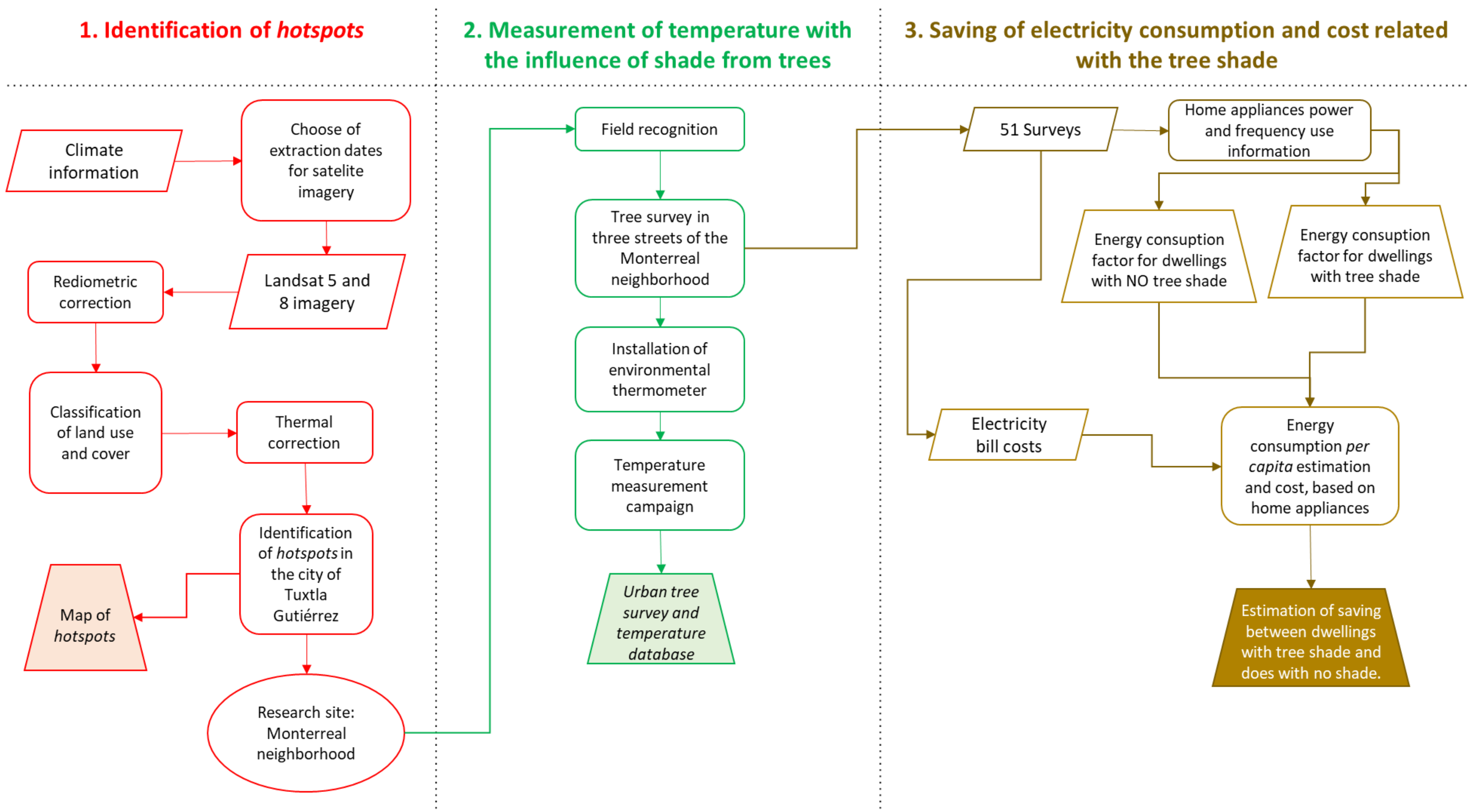

Figure 1 Diagram of the three main steps of the research and its relation.

CHAPTER I. DOES LAND-USE AFFECT THE TEMPERATURE DISTRIBUTION ACROSS THE CITY OF TUXTLA GUTIÉRREZ, CHIAPAS, MEXICO?[1]

1.1 ABSTRACT

A combination of natural (tropical latitudes) and human induced (Climate Change, Urban heat island) conditions give rise and exacerbate extreme hot temperatures, but mechanisms are unclear. Land use and land cover change (LULC) is considered one of the main causes of Urban Heat Island (UHI) but its contribution varies depending on local conditions. This study focuses on determining the influence of land use change on the UHI effect in Tuxtla Gutiérrez City by investigating the relationship between LULC and land surface temperature (LST). Through Landsat 5 and Landsat 8 imagery, this study analyzes historical LST. In 2017, the highest LST (>40 °C) occurred in the metal ceiling land class, which is made up of malls with open-air parking zones. This coverage occupied less than 3% of the total city area. Bare agriculture soil (BAS) class, located mainly on the periphery of the city, represented 11% of the city, and reported a mean LST of 35 °C, followed by asphalt roads with 34 °C and concrete ceiling with 32 °C. The lowest LST (< 28 °C), occurred in contiguous areas of trees greater than 3 ha. The LST variation when land use changed from trees to another coverage (1.3 to 3.1 °C) is higher than in the opposite direction (0.1 to 1.2 °C). The elimination or replacement of tress with impervious surfaces are the main causes for LST increase in Tuxtla Gutiérrez.

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[1] Castro-Mendoza, I., Valdez-Lazalde, J.R, Donovan, G., Martínez Trinidad, T., Plascencia Escalante, F.O., & Vázquez Morales, W. (2022). ¿El uso de suelo afecta la distribución de temperatura en la ciudad de Tuxtla Gutiérrez, Chiapas, México?. Investigaciones Geográficas, (107). https://doi.org/10.14350/rig.60394

1.2 RESUMEN

La combinación de condiciones naturales (latitudes tropicales) y antropogénicas (Cambio Climático, Isla de Calor Urbana) inducen el incremento extremo de temperatura, aunque los mecanismos no son claros. El cambio de uso de suelo es una de las principales causas de la Isla de Calor Urbana (ICU), aunque su influencia depende de las condiciones locales. Este estudio se centra en la relación del cambio de uso de suelo y la temperatura de superficie (TS) para conocer su influencia en la ICU de la ciudad de Tuxtla Gutiérrez. A través de imágenes Landsat 5 y Landsat 8, se analiza la TS histórica con el Método de Emisividad por Clasificación. En 2017, la máxima TS (>40 °C) se registró en los techos de metal de centros comerciales con estacionamientos a cielo abierto. Este uso de suelo cubre menos del 3% de la ciudad. El suelo desnudo agrícola cubre la periferia de la ciudad y representa el 11% de la ciudad, se reporta con una TS promedio de 35 °C, seguida de los caminos de asfalto con 34 °C y techos de concreto con 32 °C. La mínima TS (< 28 °C) se registra en zonas arboladas mayores a 3 ha. La variación de TS cuando se elimina la cobertura arbórea (1.3 a 3.1 °C) es mayor que cuando se reforesta (0.1 a 1.2 °C). El reemplazo de árboles por superficies impermeables es la principal causa del aumento de la TS en Tuxtla Gutiérrez.

1.3 INTRODUCTION

Human activities change weather patterns at global and local scales (IPCC, 2018), causing cities experience consistently higher temperatures than surrounding rural areas (Eniolu et al., 2013; Howard, 1988; Oke, 1982). The Urban Heat Island (UHI) effect is a pressing policy issue, because of climate change, and that 60% of the world´s population is forecast to live in urban areas by 2030 (UN, 2018) .

In Mexico, since 1990, urbanization has rapidly grown in tropical latitudes (Reyes & López, 2011). These trends of tropical urbanization and rising temperatures are seen in Tuxtla Gutiérrez (TGZ), which is the second most populated city of the Mexican tropics and house to 10% of the population of the state of Chiapas.

In the last three decades, temperatures in TGZ have risen in the dry season (De la Mora et al., 2016). However, there is little information about how much urbanization has contributed to rising temperatures and UHI impacts, people´s wellbeing, economy, and public health (López-Pérez et al., 2019; Díaz-Nigenda et al., 2018; Coello, 2015). Therefore, we examine the relationship between land-use change and extreme temperatures in TGZ.

UHI results from thermal equilibrium between atmospheric temperature (AT) and land cover with different land surface temperature (LST) (Oke, 1982). UHI intensity depends on the albedo and thermal inertia of construction materials, building density, aspect ratio, sky view factor (SVF), industrial development, traffic congestion, cloud cover, wind speed, precipitation, city geometry, and relative humidity. However, the main diver of UHI is land-use change (H. Li et al., 2018), a factor that explains about 70% of the total variance in land surface temperature (LST) (H. Li et al., 2018; Azevedo et al., 2016; Rajagopalan et al., 2014; Imhoff et al., 2010; García-Cueto et al., 2009; Britter & Hanna, 2003; Jauregui, 1997; Oke, 1973).

Recently, remote sensing data have helped UHI research by providing low-cost LST data at adequate temporal frequency (Amanollahi et al., 2016; Avdan & Jovanovska, 2016; Sobrino et al., 2004). Sensors such as MODIS (Moderate Resolution Imaging Spectroradiometer) and AVHRR (Advanced Very High Resolution Radiometer), offer thermal infrared information suitable for regional studies due to their spatial scale and spectral resolution (Amanollahi et al., 2016; Mas, 2011). Landsat imagery has been widely used at a finer scale for research

(Kato et al., 2018; Romaguera et al., 2018; Chen et al., 2017; Tan et al., 2017; Ali et al., 2016; Li et al., 2013).

LST requires information on radiance and emissivity which can be measured in situ or by remote sensing (Jeevalakshmi et al., 2017; Tan et al., 2017; Cook et al., 2014; Rozenstein et al., 2014; Yu et al., 2014; Sobrino et al., 2004, 2008). Landsat 4, 5, and 7 images have one thermal band and Landsat 8 has two. Before Landsat 8, NASA and the United States Geological Services worked to develop LST products based on the thermal archive data of Landsat missions (Cook et al., 2014). For the purpose, they automated two methods: a) Single channel technique for imagery with one thermal band, and b) Multichannel technique (Split window) for Landsat 8 (Jeevalakshmi et al., 2017; Tan et al., 2017; Cogliati, 2011; Sobrino et al., 2008; Weng et al., 2004; Olioso, 1995). The accuracy of both methods depends on the atmospheric profile information available for the scene location and scene capture time (Cook et al., 2014; Li, et al., 2013) especially for the emissivity retrieval.

Surface emissivity is a measure of the energy emitted as thermal radiation from a given land coverage (Li, et al., 2013; Sobrino et al., 2012). When measured with a remote sensor, it varies with geometry, surface materials, surface roughness, ground humidity, view angle, and atmospheric information such as relative humidity, wind speed, cloud cover and precipitation (Ermida et al., 2017; Gulbe et al., 2017; Suomi, 2014; Kahle, 1987). In absence of atmospheric information, researchers can use other methods for surface emissivity retrieval. The most common method is the Normalized Difference Vegetation Index threshold method, $NDVI^{THM}$ (Sobrino et al., 2008), which assigns an emissivity value to a given land coverage, bare soil or full vegetation, according to estimated NDVI values. However, $NDVI^{THM}$ has limitations; surfaces such as asphalt, or other common materials in urban environments, can cause inaccurate estimations of LST (Sobrino et al., 2008). A more accurate method than $NDVI^{THM}$ for urban areas is the Emissivity Classification Method (ECM), which assigns emissivity values to each land cover-land use class, based on the ASTER spectral library (ASL, https://speclib.jpl.nasa.gov/) reported by Sobrino *et al.,* (2012).

In this research the relationship between LULC and extreme temperatures in TGZ was examined. First, the surface UHI for the city of TGZ for three years (2001, 2011, and 2017) was estimated from historical analysis of air temperature. Later, Landsat 5 (TM) and 8 (OLI) imagery were used to define land use/land cover. Based on the cover types LST by ECM method was retrieved, as emissivity data were not available for the study area.

1.4 CHARACTERIZATION OF THE AREA

The city of Tuxtla Gutiérrez (TGZ) is the capital of Chiapas, a state located in southeastern Mexico between 16º 48' 46" N, 93° 13' 12" O and 16° 40' 49" N, 93 ° 02' 19" O coordinates (Figure 1.1). Elevation ranges from 435 m to 917 m. The climate is warm and sub-humid with an average annual rainfall of 915 mm the majority of which falls in the summer (INEGI, 2017). The historical records registered 19 days with temperatures above 30 °C and 25.7 days of dry conditions per year with a mean annual temperature of 25.4ºC. The hottest month is April with a mean maximum historical temperature of 45.5ºC. The city of TGZ occupies a valley surrounded on the south by Mactumatzá Hill and on the east by The Sumidero Canyon National Park; both barriers hinder air flow and influence winds from the northwest with an average speed of 9.7 km/hr, reaching gusts during winter of 36 km/hr (Díaz-Nigenda et al., 2018).

The Sabinal River crosses the city through The Sumidero Canyon National Park to the Grijalva River. The predominant types of soil are Leptosols, Regosols, Luvisol and Vertisols. The city is surrounded by 4.9 km of Natural Protected and Conservation Areas of low deciduous forest (ICIPLAM, 2013). Almost 75% of the urban flora is exotic (Román, 2017) and distributed among 193 parks and a country club (ICIPLAM, 2015).

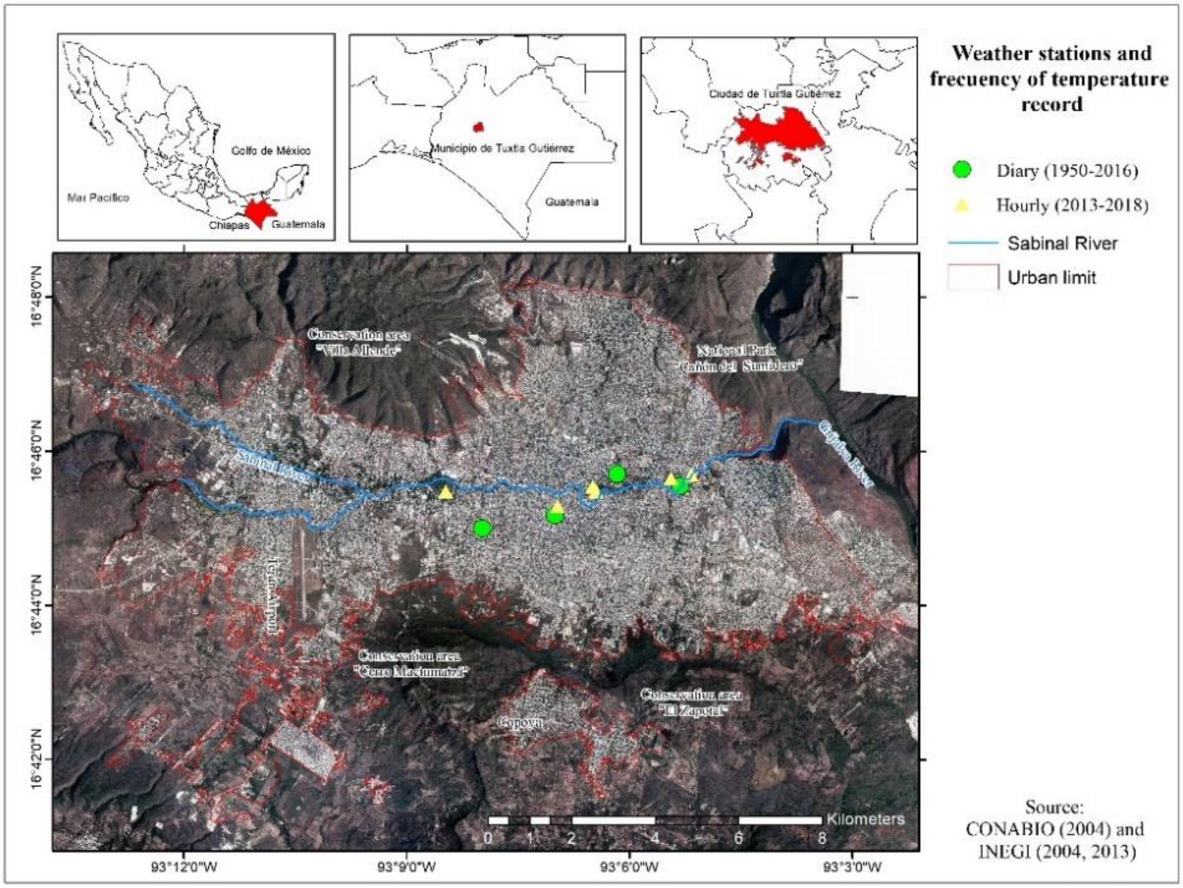


Figure 1.1 Location of weather stations in the city of Tuxtla Gutiérrez, Chiapas, Mexico.

The city, as the main economic center of the state, had a population of 537,102, in 2010, which represents an increase of 10% from 2005 (CEIEG, 2014b; INEGI, 2013) and between 2007 and 2018 it grew in area from 7.8 km^2 to 107 km^2 (HATG, 2007), an increase of 11% annually. Since 1986, residential development has an annual increase of 3% in TGZ (Silva et al., 2015). The Municipal Citizen Planning Institute (ICIPLAM) of TGZ has identified an irregular land use-land cover (LULC) change in the city since the 1980s, the one that limits urban planning and interfere with the implementation of green areas as part of urban developments (ICIPLAM, 2013) since vegetation competes with housing space.

1.5 MATERIALS AND METHODS

Data

Air temperature data from 11 weather stations (Figure 1.1) with a daily (1951-2016) and hourly (2013-2018) record were analyzed. These data were used as reference to choose the capture date of the Landsat scenes downloaded and not for the analysis of UHI in TGZ because weather stations are not evenly distributed across the city. Classification of LULC were validated in ground and with a high spatial resolution image (0.5 m) and a mosaic of orthophotos. Ground truthing of LST retrieved from Landsat images (Table 1.1 and 1.2) was done at ten verification sites in 2019, May 29th and 30th using an Extech IR201A infrared thermometer with adjustable emissivity between 15:00 and 17:00 hrs. All images were processed on ArcMap™ 10.5 package.

Table 1.1 Metadata of Landsat imagery.

Satellite	Sensor	Pixel size (m)	Nubosity (%)	Date	Hour center of the scene
LandSat 5	TM	30	5%	April 5, 2001	16: 15: 36.6920500Z
LandSat 5	TM	30	6%	April 1, 2011	16: 25: 30.5330810Z
LandSat 8	OLI_TIRS	30	0.40%	April 1, 2017	16: 35: 15.5568250Z

Table 1.2 Data used for land surface temperature (LST) retrieve at Tuxtla Gutiérrez City.

Variable	Instrument	Source	Space scale	Time scale
Daily air temperature	Four weather stations	Weather National Service	N/A	1951 to 2016
Hourly air temperature	One weather station	Electricity Federal Commission	N/A	2013 to 2016
	Five weather stations	Weather net of the Art and Science University of Chiapas	N/A	2017 to 2018
Land surface temperature	Landsat 5 scenes	US Geological Service (https://earthexplorer.usgs.gov/)	30 m	April 5, 2001 April 1, 2011
	Landsat 8 scenes		30 m	April 1, 2017
Real color image of high resolution	Unknown	Ministry of Environment and Natural History in Chiapas (SEMAHN)	0.5 m	2015
Mosaic of Panchromatic Image of high resolution	Unknown	National Institute of Statistics, Geography and Informatics (INEGI)	1.5 m	2001
Surface temperature	Infrared thermometer *Extech* brand model IR201A	N/A	N/A	Field campaign May 29 and 30, 2019

Methodology

The impact of extreme temperatures on human wellbeing and comfort was the aim of this research. Therefore, vulnerability levels due to extreme air temperatures defined by The Territory and Urban Development Ministry (SEDATU, 2014) were used as reference values for the analysis of results (Table 1.3).

Table 1.3 Vegetation and human vulnerability due to extreme air temperatures.

Temperatures	Class	Vulnerability
< 28 °C	Pleasant	Comfortable wellness
28 a 31°C	Discomfort	Evapotranspiration increases. Headaches increase in humans.
31.1 a 33°C	Extreme discomfort	Dehydration is evident. Hoppers and heavy pollution particle pollution increases, appearing at cities.
33.1 a 35°C	Stress condition	Plants evapotranspire excessively and wilt. Forest fire hazard increases.
> 35 °C	Upper tolerance limit	Heat strokes occur, with unconsciousness in some people. The diseases increase.

Most LST research has been done during the dry season because cloud cover is low and higher atmospheric humidity can increase the error of emissivity and temperature. For this reason, the research was confined to the dry season in TGZ.

To calculate LST, conventional and thermal remote sensing corrections were applied to the three scenes downloaded (USGS, 2019; Chander et al., 2009). This correction was done in two stages. First, an emissivity layer was build-up according to the ECM, then, LST was retrieved by transforming thermal brightness (Figure 1.2). The combination of band thermal and radiometric correction (Figure 1.2), allowed to obtain LST values for each image.

Though atmospheric conditions are the main source of error for LST retrieval (Cook et al., 2014), no correction of this sort was made due to a lack of information on relative humidity, wind speed, and atmospheric pressure.

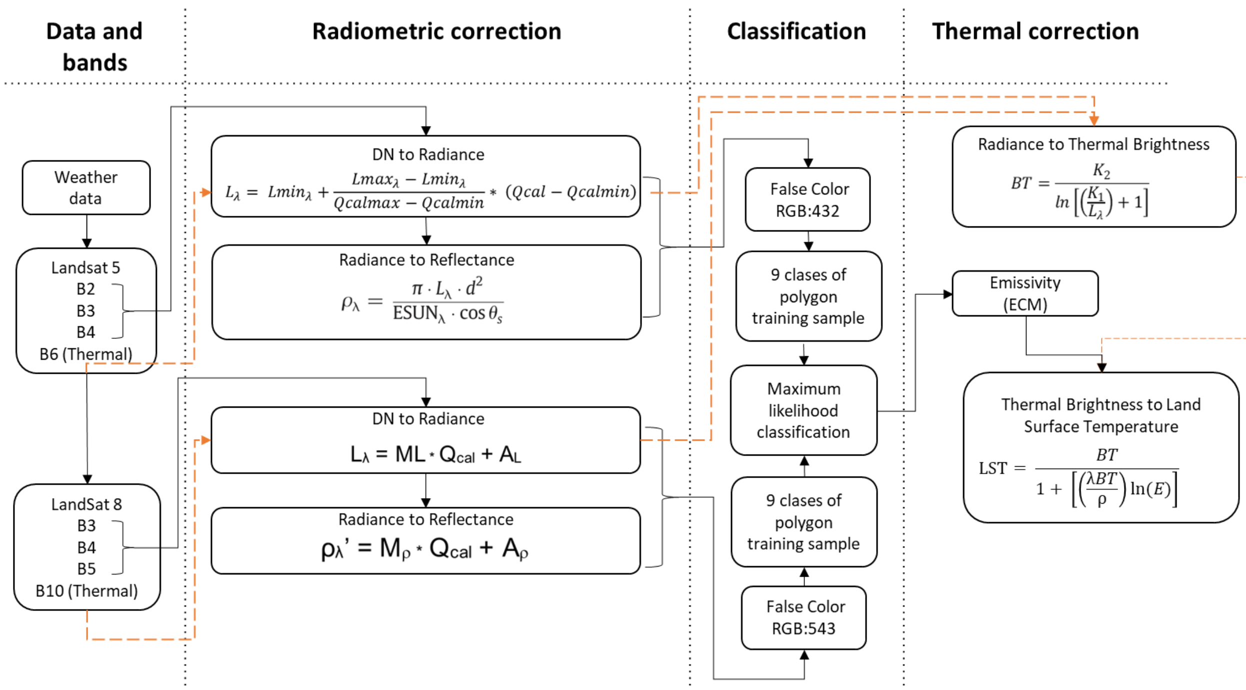


Figure 1.2 Diagram for land surface temperature (LST) retrieve based on Landsat imagery. Dash arrows indicate the band thermal correction process up to the thermal brightness while the radiometric correction and supervised classification to assign emissivity is indicated by the black arrows.

Land use-land cover image classification.

Each band of the imagery were radiometrically corrected up to reflectance (Table 1.4) using equations 1.1 and 1.2 (Chander et al., 2009). The correction served to sort the images, into nine LULC classes and thereby assign an emissivity value to each class.

Table 1.4 Radiometric correction parameters for TM 5 and OLI 8 sensors.

			TM 5 Sensor, 2001 year				
Band	**$Qcal_{MAX}$**	**$Qcal_{MIN}$**	**L_{MAX}**	**L_{MIN}**	**d**	**ESUN**	**SZ**
2	255	1	365	-2.84		1796	
3	255	1	264	-1.17	1.0005897	1536	31.31
4	255	1	221	-1.51		1031	
			2011 year				
2	255	1	365	-2.84		1796	
3	255	1	264	-1.17	0.999269	1536	30.13
4	255	1	221	-1.51		1031	
			OLI 8 Sensor, 2017 year				
	ML	**AL**	**Mp**	**Ap**	**d**		**SZ**
3	0.011861	-59.3059					
4	0.010002	-50.0101	0.00002	-0.1	0.9994378		27.84
5	0.0061207	-30.6037					

* Qcalmin = Minimum quantized value of pixel [dimensionless], Qcalmax = Maximum quantized value of pixel [dimensionless], LMIN = Spectral at-sensor radiance that is scaled to Qcalmin [W/(m2 sr µm)], LMAX = Spectral at-sensor radiance that is scaled to Qcalmax [W/(sr m2 sr µm)], ESUN= Mean exoatmospheric solar irradiance [W/(m2 µ m)], Angle SZ= Solar zenith angle [degrees] (USGS, 2019; Chander et al., 2009).

$$L_\lambda = Lmin_\lambda + \frac{Lmax_\lambda - Lmin_\lambda}{Qcalmax - Qcalmin} * (Qcal - Qcalmin) \quad \textbf{(1.1)}$$

$$\rho_\lambda = \frac{\pi \cdot L_\lambda \cdot d^2}{\mathrm{ESUN}_\lambda \cdot \cos\theta_s}$$

(1.2)

Based on a high-resolution image and the orthophoto mosaic, we generated for each image classification training polygons consisting of nine classes of LULC (Table IV). These polygons were used to train a maximum likelihood algorithm (MAXLIKELIHOOD) and classify each image (Sobrino et al., 2012; Melesse et al., 2007) .

The bare soil class denotes areas where the surface consists of bedrock (mainly limestone). The bare agriculture soil class denotes agriculture soil without vegetative cover. The rest of the classes are self-explanatory (Table 1.5).

Emissivity Classification Method (ECM)

Emissivity Classification Method (ECM), which assigns emissivity values based on previous measurements or from libraries such as the ASTER Spectral Library (ASL, https://speclib.jpl.nasa.gov/) to generate land use and land cover (LULC) classification (Sobrino *et al.,* 2012)

The ECM for emissivity retrieval were used (Table 1.5) to avoid homogenizing the entire urban area into two or three values of emissivity, which would have happened if we relied on $NDVI^{THM}$.

Table 1.5 Emissivity values by type of sensor (TM 5 and OLI 8) and LULC classes.

Sensor	TM 5	OLI 8
Band	B6	B10
Range (μm)	10.4 a 12.5	10.6 a 11.19
Water*	0.99	0.99
Trees+	0.99	0.99
Asphalt road+	0.963	0.962
Green grass*	0.981	0.98
Bare soil+	0.956	0.942
Bare agriculture soil*	0.968	0.941
Concrete ceiling+	0.957	0.943
Metal ceiling*	0.046	0.049
Roof tile ceiling+	0.942	0.939

* Source: Aster Spectral Library.
+Source: (Sobrino et al., 2012)

Land surface temperature (LST) retrieval

Once an emissivity raster coverage was estimated, LST values were obtained, following equation 1.3. Radiometric correction of thermal bands up to radiance were used. Then, using equation 1.3 (USGS, 2019; Chander et al., 2009) and conversion from Kelvin to Celsius degrees with equation 1.4, thermal brightness values from radiance was estimated.

$$TB = \frac{K_2}{ln\left[\left(\frac{K_1}{L_\lambda}\right) + 1\right]}$$

(1.3)

$$\mathrm{TB}_C = \mathrm{TB} - 273.15$$

(2.4)

Finally, per-pixel LST was calculated using equation (1.5):

$$\mathrm{LST} = \frac{TB_c}{1 + \left[\left(\frac{\lambda TB_c}{\rho}\right) \ln(E)\right]}$$

(2.5)

TB is the thermal brightness [K]; TB_c is the thermal brightness in Celsius degrees [C]; LST is the land surface temperature in Celsius degrees [C]; K_1 is the first calibration constant [W/ (m^2 sr µm)]; K_2 second calibration constant [K]; L_λ is the spectral radiance at-sensor [W/(m^2 sr µm)]; ln is natural logarithm; E is the emissivity; λ is the center of the thermal band [µm]; ρ is a constant that combines the Boltzman and Plank´s Law and the speed of light with a value of 14387.7 [µm°C] (Table 1.6).

Table 1.6 Thermal correction parameters to estimate the thermal brightness values.

	Sensor TM 5	
Band	**K1**	**K2**
6	607.76	1260.56
	Sensor TIRS 8	
10	774.89	1321.08

1.6 RESULTS AND DISCUSSION

Daily air temperature data, from 1951 to 2016, showed that after 1980 temperatures above 40 °C have become more frequent by a rate of 18% and minimum air daily temperatures above 28 °C have increased by a rate of 14%.

Hourly records from 2013 to 2018 show that maximum daily temperatures occur between 14:10 and 17:00 hrs. Daytime temperatures, between 06:00 and 19:59 hrs, range from 8.6 °C to 48.4 °C. Nighttime temperatures, between 20:00 and 05:59 hrs, range from 9.2 °C to 32.5 °C. During the time scale study, 60% of daytime temperatures and 63% of nighttime temperatures occurred between 25 °C to 30°C, suggesting that nights are as warmer as days in TGZ (Figure 1.3), but it is necessary to continue registering hourly air temperatures to confirm this trend.

As there are no weather stations located on the periphery of the city, we were unable to compare temperatures in the city center and the surrounding rural areas. In addition, there are no night Landsat images that record land surface temperature that would allow us to study diurnal variation in UHI.

On average, the hottest months, are April and May, with average daily temperature of 27.2 and 27.8 °C respectively. During these months, the maximum temperatures occur with clear skies and low relative humidity, ideal conditions for classification of LULC and LST retrieval (Figure 1.4).

This information was used to determine the Landsat scenes (Table 1.2) in order to reach an optimum accuracy of the classification processes (Table 1.7).

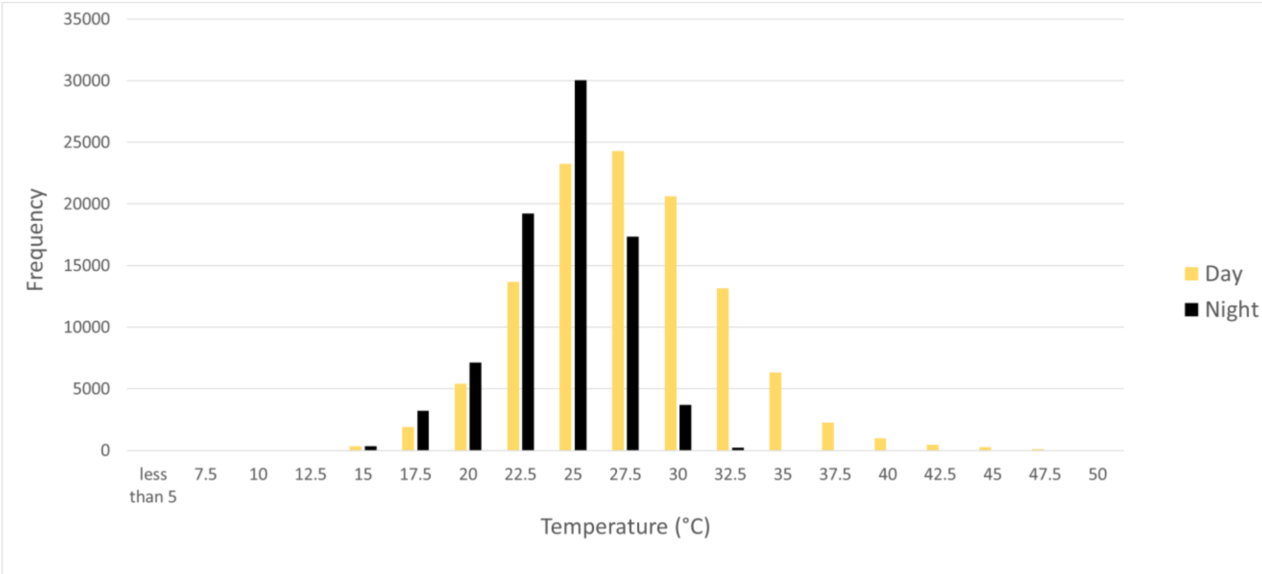


Figure 1.3 Thermal hourly distribution registered at day and night in the city of Tuxtla Gutiérrez from year 2013 to 2018.

Table 1.7 Landsat images classification accuracy

Sensor	Year	Overall accuracy(%)
TM 5	2001	80.86
TM 5	2011	86.33
OLI 8	2017	85.44

The classification processed showed that tree coverage decreased by 21% in TGZ (Table 1.8). This loss of tree cover was concentrated along the Sabinal River, Botanical Garden, Zoo, some urban parks, and natural reserves areas on the south of the city (Figure 1.6 to 1.8).

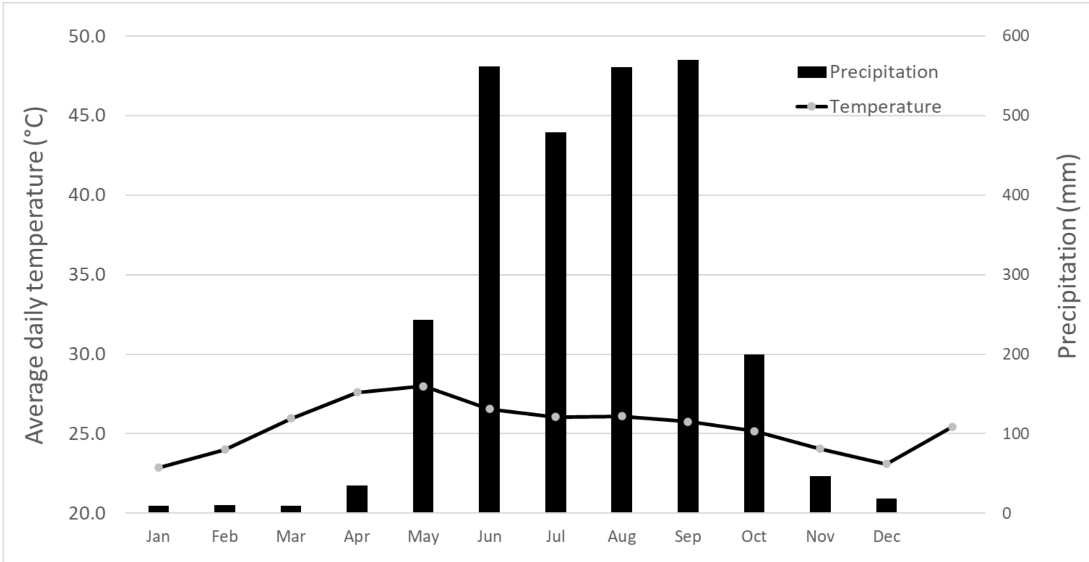


Figure 1.4 Average daily temperature and precipitation for the city of Tuxtla Gutiérrez, from 1951 to 2016 year.

Table 1.8 Land use/land cover percentage across the city of Tuxtla Gutiérrez, Chiapas in 2001, 2011 and 2017.

Class	Land coverage	2001 (%)	2011 (%)	2017 (%)
1	Water	0.02	0.01	0.02
2	Trees	17.63	14.25	13.98
3	Asphalt road	9.3	13.22	12.95
4	Green grass	1.8	2.14	1.65
5	Bare soil	2.67	4.53	7.75
6	Bare agriculture soil	34.77	20.32	11.34
7	Concrete ceiling	18.29	28.98	35.54
8	Metal ceiling	1.4	2.85	2.6
9	Roof tile ceiling	14.12	13.71	14.16

The LST distribution for the three years of the study are given in Table 1.9 and Figure 1.5.

Table 1.9 Tuxtla Gutierrez (TGZ) surface percentage per vulnerability class based on land surface temperature (LST) for the years 2001, 2011 and 2017.

	2001 (%)	2011 (%)	2017 (%)
Pleasant (<29 °C)	0.5	0.8	0.04
Discomfort (29 to 31 °C)	7.6	8	4.96
Extreme discomfort (31 to 33 °C)	31.4	30.5	47.8
Stress condition (33 to 35 °C)	30.1	36.2	32.1
Upper tolerance limit (>35 °C)	30.4	24.5	15.1

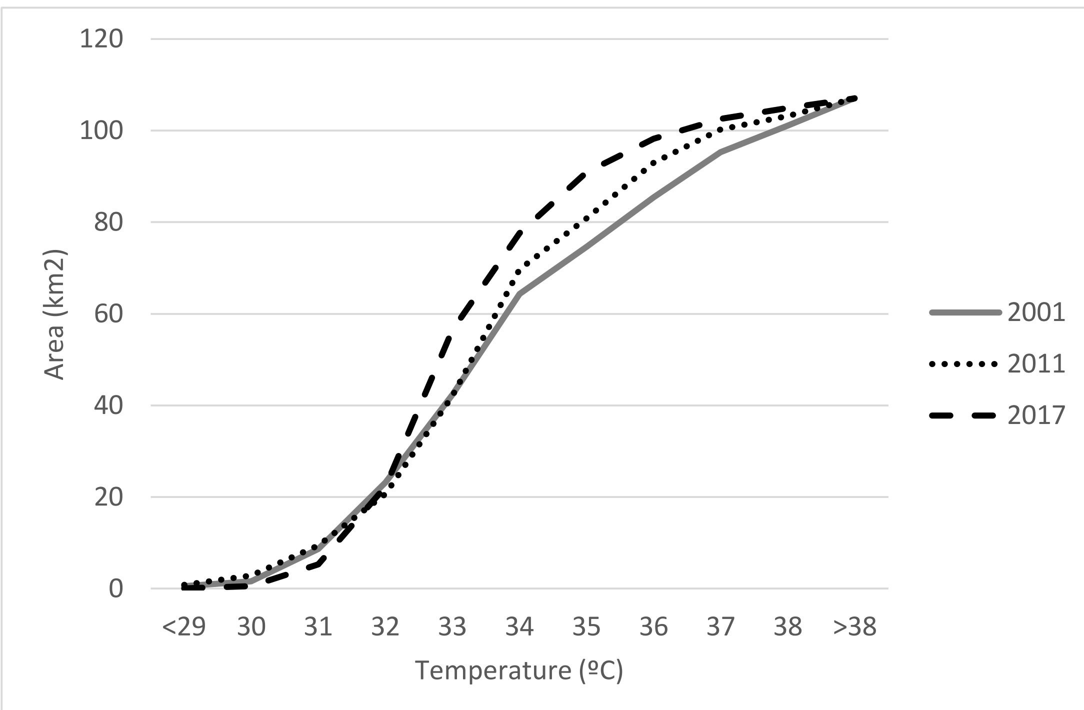


Figure 1.5 Total area for each land surface temperature (LST) range analyzed in the years of study.

There are street trees in the area but quantifying their impact on temperature and surface variation requires finer-resolution imagery, species identification and tree health recognition (Román, 2017). In the southwestern part of the city, where substantial residential development took place during the early 2000s (Silva et al., 2015), vegetation coverage has decreased and BAS, concrete, and roof tile ceiling has increased. This change in land cover was accompanied by temperature changes in TGZ. Specifically, temperatures shifted from discomfort temperatures (29° to 31° C) in 2001 to extreme discomfort (31° to 33° C) and stress condition temperatures (33° to 35° C) in 2011 and 2017, respectively.

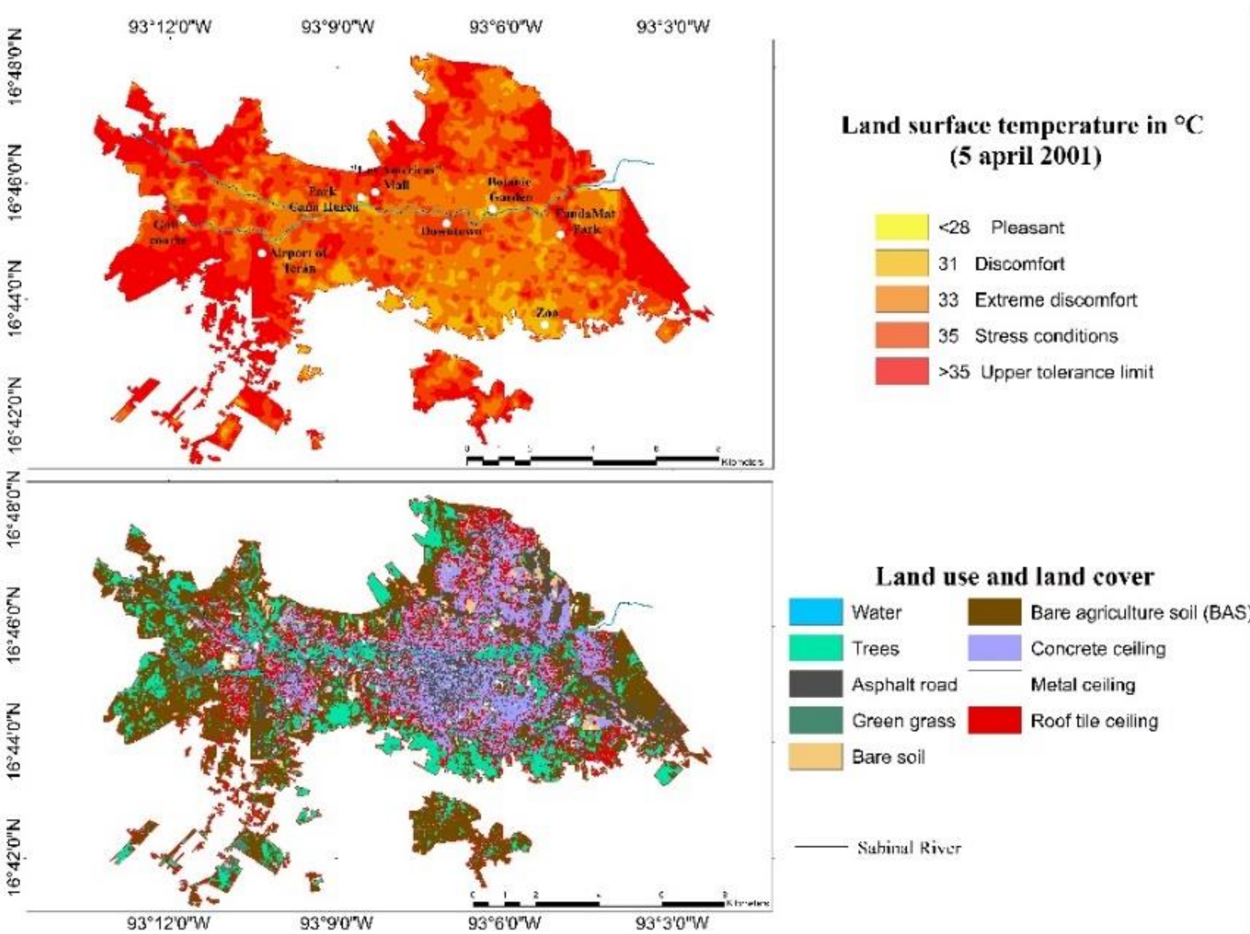


Figure 1.6 Land surface temperature and land cover during April 5th, 2001 in the city of Tuxtla Gutiérrez, Chiapas.

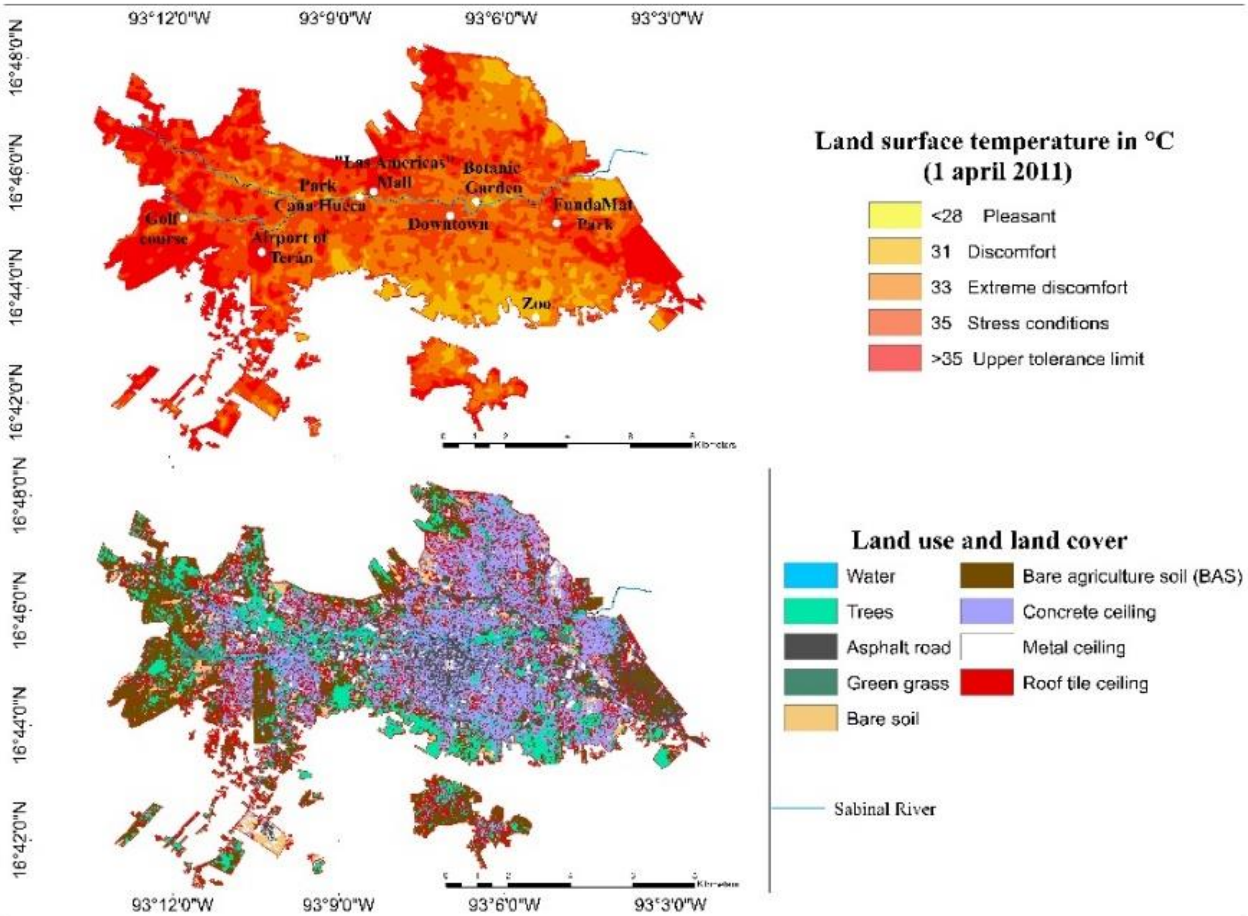


Figure 1.7 Land surface temperature and land cover during April 1st, 2011 in the city of Tuxtla Gutiérrez, Chiapas.

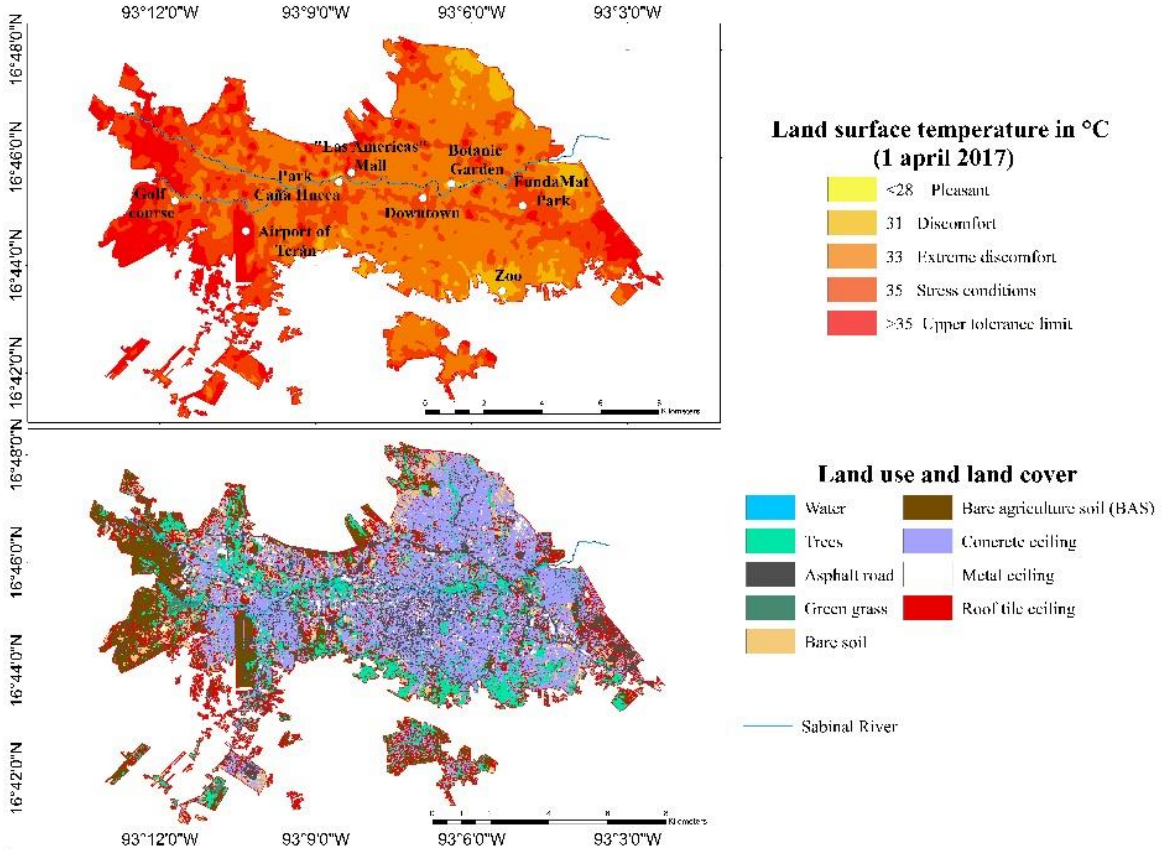


Figure 1.8 Land surface temperature and land cover during April 1st, 2017 in the city of Tuxtla Gutiérrez, Chiapas.

The urban tree land-cover class had the lowest LST. In 2001, around 25% of urban tree areas were located at pleasant to discomfort temperatures zones, reaching only 11% by 2017. Large continuous areas of dense tree cover had the lowest LST, for example, parks such as Caña Hueca, Joyyo Mayu, Tuchtlán, Botanical Garden, Parque Oriente and Parque Patricia, with areas from 3 to 20 ha, registered temperatures below 28 °C LST. By contrast, parks smaller than 3 ha or with very dispersed and low tree density, such as urban parks or wasteland (1.3 to 13.3 ha), had higher temperatures (Figure 1.9). It is evident at the spatial scale of the present study, that the Sabinal River has a cooling effect (Figure 2.6 to 2.8), which crosses the city in the west-east direction, and its riparian vegetation. For the three years analyzed, we observed that along this main-channel, and in its open sky sections the maximum temperatures ranged from

28 to 35 °C. We observed, the same mitigating effect in other tributary channels to the east of the city.

Figure 1.9 Comparison of land surface temperature (LST) registered at two contiguous woodland areas with different tree density.

The BAS class is made up of dark soil clays (mainly Vertisols, Regosols, and Leptosols) devoid of vegetation that is distributed at the periphery of the city. Its extent decreased 67% (3,650 to 1,214 ha) between 2001 and 2017, changing into roof tile ceiling, asphalt road, and concrete ceiling classes. For the three years analyzed, BAS mean temperature was 35 °C, but when it changes into asphalt road its mean value decreased 1 °C for and 3 °C for concrete ceiling. Thermal characteristics of soil and the day/night behavior of UHI highly influence the BAS class.

Soil physicochemical characteristics determine its capacity to absorb and retain heat. Dark and damp soils with high organic matter content tend to retain a greater amount of caloric energy and lose it more slowly. By contrast, light, stony and dry soils have a heterogeneous behavior; they can be heated considerably but also lose energy quickly or absorb it at lower rates and therefore show less caloric emission (Owens & Rutledge, 2005). Climate also influences soil temperature; in tropical regions soils tend to have higher temperatures (from 2 to 4 °C above the AT), due to microbial activity, compared to soils of the same type in temperate regions (Buol, 2005).

Vertisols are dark soils, with a high content of clays considered isohyperthermic, thermal and mesic (IUSS, 2007; Palma-López et al., 2002; Virmani et al., 1982). These are the type of BAS that presents the maximum retrieve LST for the three dates of the present study. They are located on the west of the city, as temporary agricultural land at rest; that is, without crops at the time the images were acquired. During field verification moisture and stubble were observed. This land use faces conversion pressure, as 11 residential developments were registered nearby.

Leptosols and Regosols are shallow, stony, grouped as Entisols, and are considered hyperthermic and thermal soils (IUSS, 2007; Palma-López et al., 2002; Lorenz, 1995). Leptosols are located on the north and east of the city on steep slopes. Between 2000 and 2015 these areas showed the greatest urban sprawl and land conversion. Now, however, they are areas of conservation. On the other hand, Regosols are located on the south of the city. Their thermal behavior is the most heterogeneous. They register temperatures lower than 28 °C to 39 °C. Possibly due to the stony conditions, Regosols´ temperature rises considerably during the day, but drops quickly in cloudy conditions, or at night. However, this behavior has not been verified since there are no Landsat scenes of the study area at night.

The physical characteristics of each land coverage are also related to the day/night behavior of UHI, a phenomenon that has been extensively discussed (Kato et al., 2018; Ando & Ueyama, 2017; Azevedo et al., 2016; Prakash et al., 1999; Jauregui, 1997; Oke et al., 1991). Bohnenstengel et al., (2011), simulated the behavior of the UHI in the city of London, evaluating the energy flow hourly. The study found that the temperatures of rural and urban areas depend on thermal inertia. Usually, thermal inertia of rural areas is low. Increasing LST in rural areas, requires less energy than doing so urban areas. Nevertheless, diurnal behavior of both areas, rural and urban, depends not only on thermal inertia but also on cloudiness, relative humidity, direction and speed of wind, and constructive materials. Similar observations in Arizona and Mexico City where peri urban areas recorded higher temperatures than cities´ downtowns during the day and the inverse behavior at nights (Ruddell & Dixon, 2014; Imhoff et al., 2010; Tejeda-Martínez & Jáuregui-Ostos, 2005; Jauregui, 1997).

Areas with both, metal ceiling and asphalt roads, such as malls like Plaza de las Americas, Plaza Cristal and Plaza Polyforum showed thermal peaks (temperature above 40°C). These results described are consistent with those reported by Coello (2015) who used a thermographic camera to retrieve temperatures for different coverages at the main campus of The University of Science and Art of Chiapas between 13:00 and 15:00 hrs. Coello reported that maximum temperatures occurred at the metal ceiling of sport courts (60.5 °C), followed by football camp with synthetic grass (55 to 59 °C), bare soil with the large range of temperature variation (46 to 58 °C), asphalt roads (52 to 57 °C), concrete (47 to 54 °C), scattered vegetation (33 to 38 °C) and swimming pool (28 to 29 °C) (Coello, 2015).

One transect profile was generated across TGZ form east to west direction to validate the changes in LST due to of land cover changes occurring from 2001 to 2017 (Figure 1.10). LST has increased due to transformation of trees into SDA or non-evaporating surfaces and decreased when land converted to trees (Table 2.10).

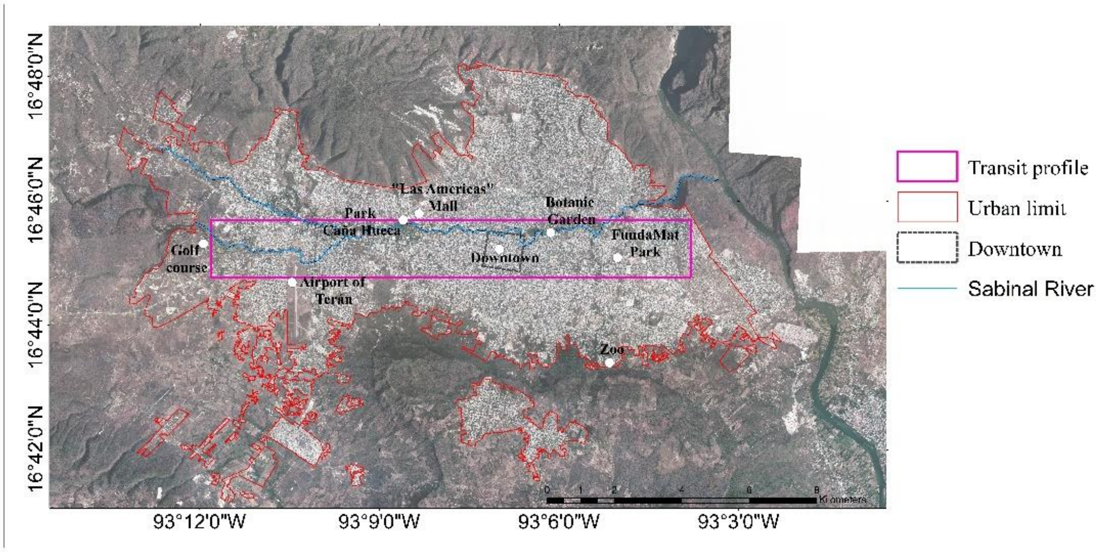


Figure 1.10 Transect profile across the city of Tuxtla Gutiérrez, Chiapas used for validating the relation of land surface temperature (LST) with land use and land change cover.

The mean temperatures reported at Table 1.10 were those occurring at transect profile (Figure 2.10). The highest increase in LST occurred when trees became BAS (3 °C), followed by asphalt road (1.7 °C) and bare soil/concrete ceiling (1.4-1.3 °C). On the other hand, TGZ city had reforestation programs at median strips, parks and vacant lots in 2005 and 2016, and these programs appear to have a modest cooling effect flourishing (0.1 and 1.2 °C) by 2017 year.

On the 29th and 30th of May 2019 (Table 1.11) between 15:00:00 and 17:17:00 hrs, temperature verification performed in 10 sites across the city of TGZ. The sites were chosen considering the areas that reported high LST during 2017. May 29th presented sunny conditions, while May 30th was cloudy with drizzle. On both dates, the maximum temperatures were recorded on site 03, in the east of the city, which had BAS Leptosol with pebbly black earth. The second highest temperatures appeared on site 02, in the west, with BAS Vertisol and black soil with residual stubble. Synthetic pit grass was the second warmest coverage, followed by asphalt. Direct temperature measurement showed the same relative patterns, although there were some differences between directly measured and remotely sensed temperatures.

Table 1.10 Land surface temperature (LST) variation in response to land use/land cover changes

Land use/land cover change	Area (ha)	Mean Temp. (°C) 2001	Mean Temp. (°C) 2017	Average change in LST (°C) 2001-2017
Tree to asphalt road	30.33	32.27	33.99	1.7
Tree to bare soil	21.69	32.27	33.64	1.4
Tree to BAS	13.23	32.27	35.34	3.1
Tree to concrete ceiling	64.7	32.27	33.6	1.3
Asphalt to tree	6.8	33.1	32.9	-0.1
BAS* to tree	20.5	35	33.8	-1.2

*BAS = bare agriculture soil

Notwithstanding, this study was limited by the resolution and only daytime availability of the satellite imagery, the previous studies (Coello, 2015) and verification performed supported the trend of the different land uses and coverages in relation with LST. The direction of land use change determines the raised or decreased of LST, but in general, when vegetation is transformed into any other land use the LST increased at least 1 °C and decreased the same in the opposite direction. The minimum variation of LST detected in land use change from asphalt to tree (-0.1 °C) may be caused by the imagery resolution

(30 m per pixel) and height of trees, since reforestation programs are recent, and according to Coello (2015), the refreshing effect of vegetation may be more than 10 °C in comparison with asphalt and BAS cover.

The cooling effect of vegetation in tropical cities may contribute to the wellbeing of the population by mitigating UHI, but more studies are needed in economic and social terms in each city for a strategy to determine the sites and area of reforestation, the maintenance work required, the best species for reforestation and the availability of soil and water needed.

1.7 CONCLUSIONS

For the city of TGZ, the materials with the highest thermal sensitivity were BAS and asphalt roads. The change of tree cover into asphalt road, bare soil or BAS cover caused LST increased 1 °C to 3 °C. When asphalt or BAS cover classes turned into the tree class, LST decreased from 0.1 °C to 1 °C, suggesting that the cooling effect of trees is not immediately reached after reforestation. The vegetation effect in LST is appraised if woodlands are greater than 3 ha indicating a limitation of the analysis caused by the spatial resolution of the imagery used.

The ECM for the thermal assessment captured the surface heterogenicity of the TGZ city avoiding underestimations induced for NDVI methodologies. Nevertheless, the *in-situ* measures of emissivity values and night temperature assessment will improve results and are desirable for further investigations.

The approach implemented in this study to carry out the analysis could be used to evaluate the surface thermal dynamic of cities when monitoring weather networks are not available or are not wide enough to cover the study area properly.

Table 1.11 Land surface temperatures at verification sites

Site	Colony	Description	Latitude	Longitude	Temperature (°C) 29 May	30 May	Notes
UNICACH, University City	Canteras	Football field	16.78	-93.12	45.0	34.0	Synthetic open pit grass
SEMAHN	Rivera Cerro Hueco	Parking lot	16.73	-93.09	43.7	32.3	Asphalt and stone
Market Dr. Rafael Pascacio Gamboa	El Calvario	Market with metal ceiling	16.75	-93.12	45.0	34.7	Area with high vehicular traffic and little vegetation cover
Plaza Del Sol (De las Américas)	Joyo Mayyu	Parking lot	16.76	-93.14	40.8	35.3	Asphalt
Terán airport	Militar base air	Hill with bare soil vertisol	16.74	-93.18	43.8	34.1	Constant burning for weed management, vertisol, black soil

Site	Colony	Description	Latitude	Longitude	Temperature (°C) 29 May	30 May	Notes
Site 01	Nameless	Burned agricultural field	16.77	-93.20	42.5	33.8	Bare regosol, brown soil
Site 02	Nameless	Agricultural field without stubble	16.74	-93.22	49.6	40.3	Bare vertisol, black soil
Site 03	Satélite (Loma Larga)	Base soil	16.74	-93.05	50.7	48.0	Bare leptosol, black soil, stony
UNICACH, Plastic Arts Campus	Tzocotumbak	Football field	16.75	-93.10	41.0	37.1	Synthetic open pit grass
Road	Road to Vicente Guerrero	Asphalt	16.74	-93.21	46.8	36.8	Asphalt road near vertisol soil fields

CHAPTER II. DOES TREE SHADE HELP MITIGATE HIGH TEMPERATURE OF HOUSES IN TROPICAL CITIES?

2.1 ABSTRACT

In Mexico there is little research regarding to the benefits of urban forests. The present work analyzes dwelling and sidewalk temperatures in direct sunlight versus with the influence of tree shade in the Monterreal neighborhood at the city of Tuxtla Gutiérrez (TGZ), Chiapas, México. The purpose is to know to what extent urban trees reduce extreme temperatures.

Tree shade can reduce both, atmospheric and surface temperatures. Tree shade reduced the surface sidewalk and exterior wall temperature by 26.5 °C and 6 °C, respectively. In the case of air temperatures, tree shade reduced temperature next to an exterior wall by 3.43 to 3.99 °C and reduced temperature next to an interior wall by 0.96 to 1.25 °C.

A recommendation for dwellings to reduced exterior and interior temperature is to plant trees with globose crown shape at the east side of the house and paint exterior walls with white or clear colors.

2.2 RESUMEN

En México se conoce poco de los beneficios relacionados con los bosques urbanos. El presente trabajo analiza las temperaturas de las viviendas y aceras bajo la luz solar directa versus la influencia de la sombra de los árboles en la colonia Monterreal de la ciudad de Tuxtla Gutiérrez (TGZ), Chiapas, México. El propósito es saber en qué medida el arbolado urbano reduce las temperaturas extremas.

La sombra de los árboles puede reducir tanto la temperatura atmosférica como la superficial. Encontramos que la sombra de los árboles redujo la temperatura de la superficie de la acera y de la pared exterior en 26.5 °C y 6 °C, respectivamente. En el caso de las temperaturas del aire, la sombra de los

árboles redujo la temperatura junto a una pared exterior entre 3.43 y 3.99 °C y la temperatura junto a una pared interior entre 0.96 y 1.25 °C.

Una recomendación para viviendas con temperatura exterior e interior reducida es plantar árboles con forma de copa globosa en el lado este de la casa y pintar las paredes exteriores de color blancos o claros.

2.3 INTRODUCTION

The increase of temperature in urban environments is mainly induced by two phenomena: Climate Change (CC) and the Urban Heat Island (UHI). It is difficult to distinguish in what proportion each one influences the urban temperature condition. Now a day, the social implication of these combination affects more than half of the world's population and is expected that the value will be 70% by 2050 (Stone et al., 2012; TWB, 2010). Considering the last, population is increasingly concentrated at cities with scarce planning, resources and conditions for expansion unable to grant the wellbeing for new residents.

In tropical countries, so as the south of Mexico, more intense or more frequent extreme temperatures will have both economic and health consequences (Méndez-Lázaro et al., 2018; Donovan et al., 2013; Dell et al., 2012; Jáuregui, 2005; Gutiérrez, 2003). Some temperature mitigation strategies for cities had been developed, such as green roofs, highly reflective surfaces coating and tree cover (Shafique & Kim, 2017; Vazquez et al., 2016; Mildrexler et al., 2011; TWB, 2010; Rizwan et al., 2008; Emmanuel et al., 2007; Rosenfeld et al., 1995), but the use of trees as temperature regulators has been quiet successful considering the benefits in other ecosystem services such as pollution removal, carbon storage, increased biodiversity, hydrology effects among others widely documented in cities around the world (Zhang et al., 2015).

In Mexico there is little research regarding the benefits of urban forests. Most studies of trees as a temperature buffer have been focused on Mexico City (Cui & de Foy, 2012). However, the spatial scale used in the analysis, a pixel of 1 km by 1 km, is too coarse to capture the effect of individual trees. In cities such as Querétaro, Puebla, Guadalajara and Mérida, research has been carried out with transect and plot techniques, as well as thermal remote sensing. The results confirm that forest areas mitigate air temperatures between 2.05 and 4 °C (Gomez-Martinez et al., 2021; Palafox-Juárez et al., 2021; Colunga et al., 2015; Rivera, 2012; Bello-Fuentes, 1994). However, as with the research in Mexico City, these studies do not focus on the effect of individual trees, which can reduce the surface temperature between 25 and 11 °C according to studies in cities of Italy, Turkey, and the United States of America (Napoli et al., 2016; EPA, 2008; Yilmaz et al., 2008).

The present work analyzes dwelling and sidewalk temperatures in direct sunlight versus with the influence of tree shade in the Monterreal neighborhood at the city of Tuxtla Gutiérrez (TGZ), Chiapas, Mexico; this area is considered a *hot spot* due to its extreme temperatures during the hot season (Castro-Mendoza et al., 2022). The purpose is to know to what extent urban trees reduce extreme temperatures on common surfaces in the city, the sidewalk, and the exterior/interior dwelling front wall of residential building. Knowing these data helps to stablish the scope of individual trees as a temperature mitigator which could step up urban reforestation programs at the city.

2.4 CHARACTERIZATION OF THE AREA

The city of Tuxtla Gutiérrez (TGZ) is the capital of the state of Chiapas, in the Mexican southeast; the city covers 40% of the municipality and is located between the coordinates 16º 48' 46” N, 93º 13' 12” W and 16º 40' 49” N, 93º 02' 19” W. The altitude ranges from 435 to 917 m and the climate is warm and subhumid with rains in summer (CEIEG, 2014a). The rainy season runs from May to October, and the average annual rainfall is 951 mm. The average annual temperature is 25.4°C, with the hottest months being April and May with maximums of up to 45.5°C. The city is divided by the Sabinal River and has 10 tributary streams, which flows into the Sumidero Canyon National Park and then into the Grijalva River. The city is surrounded by 4.9 km ^{2} of Natural Protected and Conservation Areas: “Cerro Mactumatzá”, “El Zapotal” Recreational Ecological Center, the “Villa Allende” Forest Zone, and the “Cañón del Sumidero” National Park (ICIPLAM, 2013). These areas contain native deciduous forest, while 75% of the urban trees are exotic (Román, 2017)and are distributed mainly in 193 gardens for public use and a country club (ICIPLAM, 2015).

The city has expanded rapidly as it is the main economic and service center of the state. From 2007 to 2018 its area increased from 7.8 km^2 to 107 km^2 (HATG, 2007), an approximate annual increase of 11%. This expansion is mainly caused by urban residential developments with few ecological regulations.

The study focused on the Monterreal colony located north of TGZ. It was formerly identified as a *hot spot* inside the city (Castro-Mendoza et al., 2022) and has an area of 0.28 km ^{2}. The dwelling development has 967 houses of approximately 180 m^2 each one, with the same construction plan, although some have been modified by their owners. Construction materials consist of solid concrete and bricks covered with plaster and paint. There are three areas of bare soil, a wasteland lot at the beginning of the neighborhood that adjoins Av. Laguitos with an area of 3.1 ha, Parque de las Serpientes with 0.63 ha and Parque Monterreal with 1.19 ha. These areas have little or no vegetation, which is the reason for accumulating a large amount of heat provided by the Sun during the day and for being considered a *hot spot* (Figure 2.1).

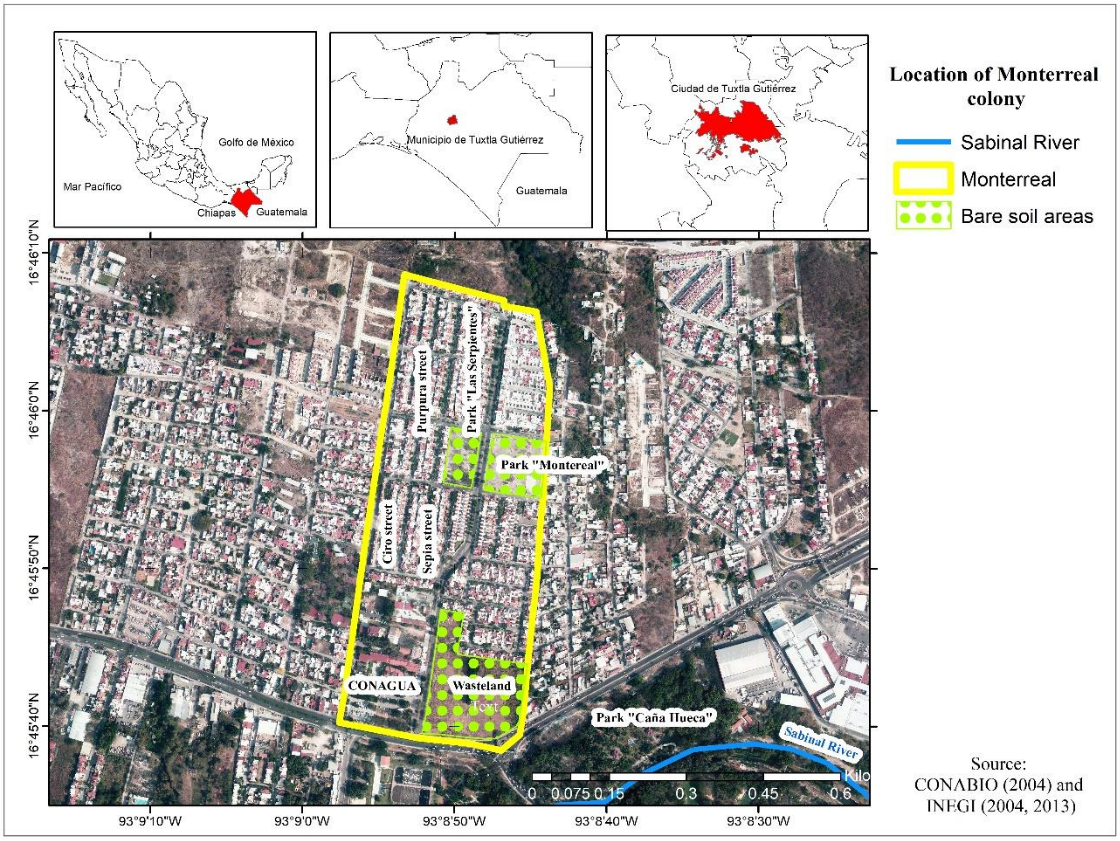


Figure 2.1 Location of the Monterreal neighborhood in the city of Tuxtla Gutiérrez, Chiapas, México.

2.5 MATERIALS AND METHODS

The general steps that were followed in this study are expanded below (Figure 2.2). The field recognition began in 2019, and the tree survey in 2021, where equation 2.1 was used to calculate the sample size.

$$n = \frac{Nz^2pq}{(N-1)E^2+z^2pq} \qquad \textbf{(2.1)}$$

Where n is the sample size to survey, N is the total number of trees (689) in the Monterreal neighborhood, E is the level of significance (0.15), z is the statistic power (1.96) and p and q constants (0.5 respectively).

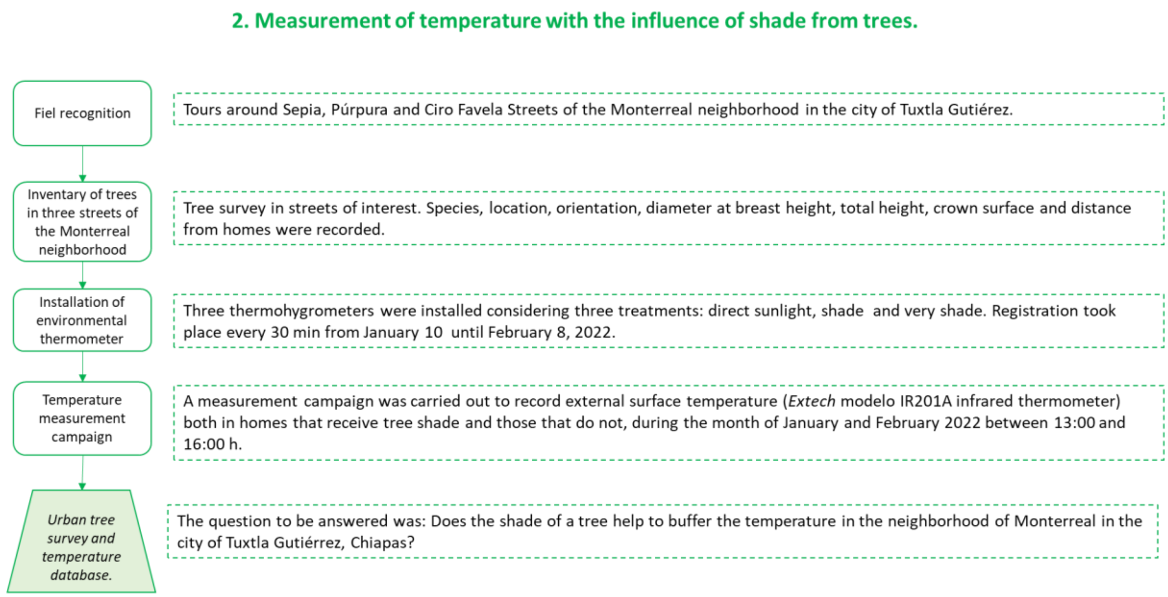


Figure 2.2 General methodology follow to measure the exterior and interior temperature of dwellings in order to determine the influence of the shade of trees.

The tree survey was done along three streets across of the Monterreal neighborhood in a North-South direction: Sepia, Purple and Ciro Farrera. Tree species, location, diameter at breast height (DBH), total height, crown surface and height, basal area, shape factor, total volume, tree orientation in relation to house location (Figure 2.3) and distance (distance from tree to house) were measured for all sampled trees.

The DBH was determined with a diametric tape while the total height, crown height and the distance from the tree to the house was measured with a SNDWAY™ SW-800b rangefinder. To calculate tree basal area (g), total volume (v) and crown surface, equations 3.2 and 3.3 were used.

$$g = \left(\frac{\pi}{4}\right) * d^2 \qquad \textbf{(3.2)}$$

Where g is the basal area expressed in m ^{2} and d the measured DBH.

$$v = g * f * a \qquad \textbf{(3.3)}$$

Where v is the total volume in m ^{3}, g is the basal area, f is the shape factor and a *is* the total height in m. For the crown surface, the ellipse formula was considered.

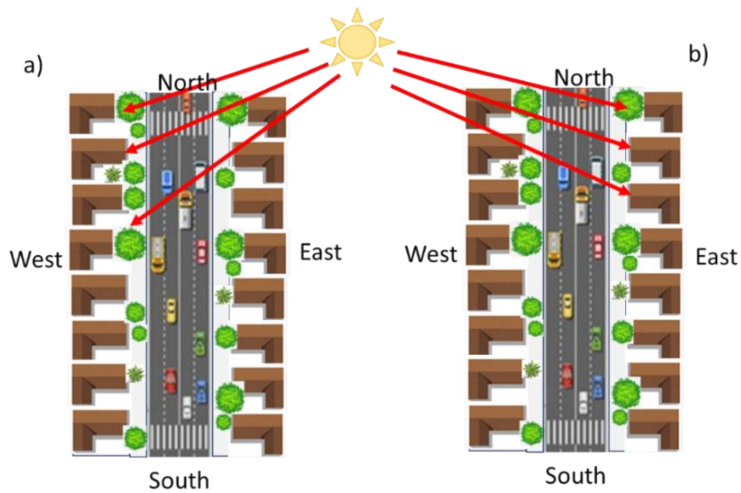


Figure 2.3 a) East orientation and b) West orientation for tree and house front.

The temperature data were measured by two methods. The first method retrieved exterior surface temperature with a surface thermometer *Extech™* Pocket model IR201A with adjustable emissivity. Temperature was measured on four days: January 21st and 25th and February 2nd and 7th, 2022. All days were sunny with ambient temperatures above 34°C. The temperature measurement points to observe the effect of tree shade followed the survey sampling. In total, four measurements were made per point, two in direct sunlight and two in the shade, both on the sidewalk and on the wall. The direct sun measurement temperature was made on the sidewalk or wall of the house no more than 1 m from the end of the tree shade. In the case of the floor, it was measured on the same type of surface, so the materials and color were the same for all measurements.

The position of the tree with respect to the house, total tree height, the color of the fence or wall of the house and measurement time, between 12:00 and 16:00 h, during the maxima thermal (Castro-Mendoza et al., 2022) were also recorded.

Besides, qualitative assessments of leafiness and tree pruning were noted for each tree.

Data processing was done on RStudio™ version 2021.09.2 (PBC, 2022). Mean sidewalk and wall temperatures under sunny and shaded conditions were compared using the Students´s t-test method with a significance level of 95%, after verifying that the data meet a normal distribution, were independent and had homogeneity of variance.

The second method used three thermometers (Figure 2.4) for internal and external air temperature measurements of three houses and were installed on January 10th and February 8th, 2022. These measurements were used to study the effect of exterior temperature and conditions over in-house temperature. Two devices were installed in shaded and very shaded wall conditions and the other one in a wall without influence of tree shade. The three walls where the devices were installed had an east orientation.

Figure 2.4 Thermometer installed to measure wall internal and external air temperature at Monterreal houses.

The construction materials of the three houses were the same. Specific characteristics are described in Table 2.1.

Table 2.1 Characteristics of the houses where thermo-hygrometers were installed.

	Shade condition	Orientation	Tree	Color of exterior paint
House 1	Direct sun	East	None	White
House 2	Shaded	East	Benjamina fig	White
House 3	Very shaded	East	Benjamina fig Moringa	Blue

2.6 RESULTS AND DISCUSSION

Tables 2.2 and 2.3 show the results of the survey carried out in the Monterreal neighborhood. Following equation 3.1, the sample size for the survey was identified as 45 trees; however, 55 more trees were considered for a total of 100 trees surveyed. Figure 2.5 shows the spatial location of the surveyed trees in the neighborhood.

Table 2.2 Survey of urban trees in the Monterreal neighborhood.

Family	Common name	Species	Number of trees
Arecaceae	Florida royal palm	*Roystonea regia* Kunth	7
		Dypsis lutenscens (H.Wendl .) Beentje & J.Dransf	1
Bignoniaceae	Yellow bells	*Tecoma stans* L.	1
Combretaceae	Country almond	*Terminalia catappa* L.	5
Cupresaceae	Italian cypress	*Cupressus sempervirens* L.	10
Fabaceae	Flamboyant	*Delonix regia* (Bojer) Raf .	1
Malpighiaceae	Nance	*Byrsonima crassifolia* L.	2
Moraceae	Benjamina fig	*Ficus benjamina* L.	64
Moringaceae	Moringa	*Moringa oleifera* Lam.	3
Nyctaginaceae	Bougainvillea	*Bougainvillea attractiveness* Willd .	1
Oleaceae	Chinese privet	*Ligustrum lucidum* W. T. Aiton	1
Rutaceae	Lemon	*Citrus aurantifolia* (Christ) Swingle	4

Table 2.3 Height, volume and crown cover of urban trees surveyed in the Monterreal neighborhood.

Common name	Mean height (m)	Mean volume (m^3)	Mean canopy surface (m^2)
Country almond	2.24	0.02	7.26
Benjamina fig	3.80	1.44	20.73
Bougainvillea	2.60	0.02	4.51
Yellow bells	2.22	0.01	5.00
Italian cypress	5.15	0.03	0.57
Flamboyant	2.30	0.02	5.10
Lemon	2.00	0.03	6.40
Moringa	2.93	0.08	16.98
Nance	2.49	0.36	27.66
Florida royal palm	3.51	0.05	6.57
Chinese privet	1.00	0.01	3.41

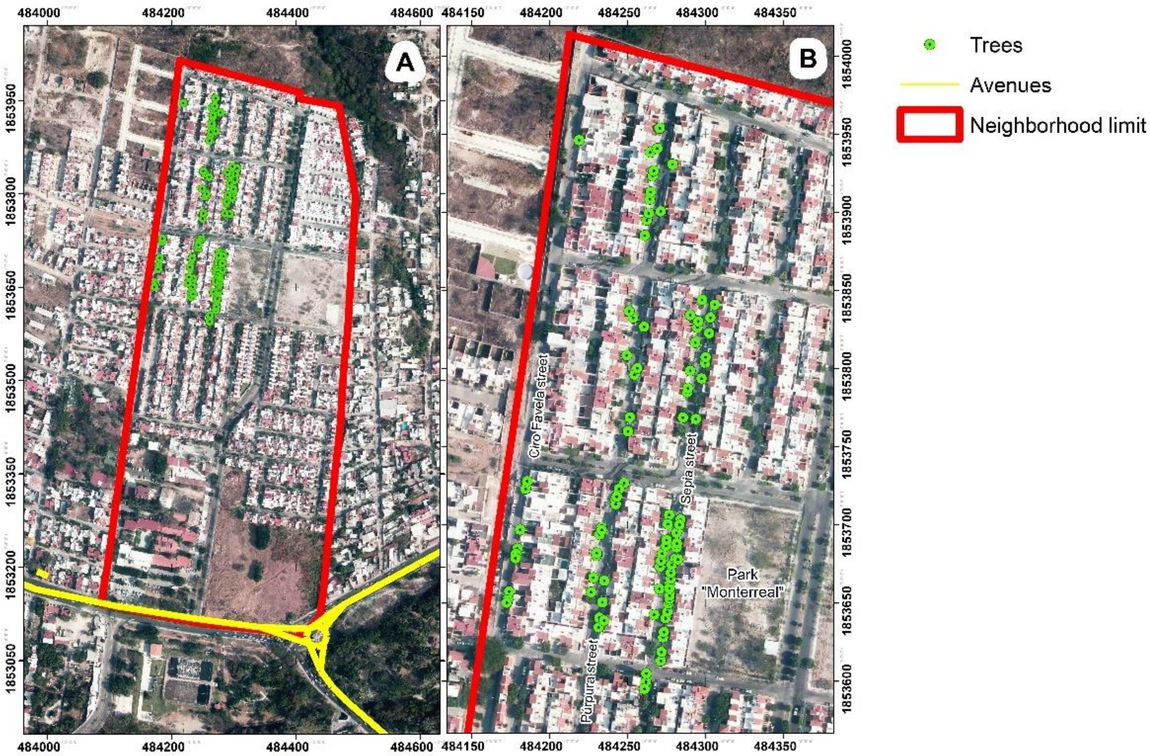


Figure 2.5 Location of surveyed trees in the Monterreal neighborhood. A) general view of the neighborhood. B) Close view of surveyed trees.

Benjamina fig tree is the dominant species, representing 64% of the trees in the study area. The species has wide crown and abundant foliage, unfortunately the crown is usually modified through pruning, although within the neighborhood they retain their globular, cubed appearance, producing broad shade that cover an average of 20.73 m^2. The tallest recorded specimen reached 8.4 m and the smallest half a meter. Meanwhile, the Italian cypress has a presence of 10% in the neighborhood, making it the second most abundant species. The height ranges from 10.5 m to 2.67 m, its crown is elongated, having a coverage of 0.57 m^2 so the shade generated is few.

The distance of trees to houses is an important component for this type of analysis (Hwuang et al., 2016; Hwang et al., 2015; Donovan & Butry, 2009) but it was not considered for Monterreal neighborhood since 90% of them are at 5 m from houses. Besides the temperature of the sidewalk in direct sunlight is on average 26.5 °C higher than the temperature on a shaded sidewalk, while for the wall the difference is only 6 °C (Table 2.4). These temperature differences are slightly higher than those previously reported (Speak et al., 2020; Napoli et al., 2016; Berry et al., 2013); however, the city of Tuxtla Gutiérrez has a tropical climate.

Table 2.4 Descriptive statistics of sidewalk and wall temperature in direct sunlight and with the influence of tree shade.

Statistical	Sidewalk temperature (°C)		Wall temperature (°C)	
	Sunny	**Shaded**	**Sunny**	**Shaded**
Mode	49.3	20.8	27.9	22.7
Median	51.07	24.17	30.53	25.33
Mean	**51.17**	**24.62**	**31.53**	**25.51**
Std. Des.	4.03	2.56	5.55	3.13
Variance	16.31	6.57	30.81	9.84
Maximum	57.2	30.5	43.5	32.87
Minimum	42.93	18.43	21.27	19.8
Range	14.27	12.07	22.23	13.07

Napoli et al. (2016) measured the difference in surface temperature between asphalt and grass when they were shaded by trees in Florence, Italy. The results indicated that on asphalt, tree shade reduced surface temperature 22.8 °C. A similar temperature reduction was registered in Bolzano, Italy (Speak et al., 2020), where average surface temperature cooling was between 16.4 to 19 °C, and at Melbourne, Australia the reduction average temperature of houses that were shaded by trees was 9 °C (Berry et al., 2013).

Temperature in direct sunlight and in the shade of the tree were significantly different ($P<0.001$) and therefore the tree shade is a factor that buffers the temperature in the sidewalk. A similar result was found for the wall temperature. However, in the last case is difficult to determine that the quality of the tree shade is the only factor. Although all the houses have the same construction materials, the coverage (paint) was different, in addition to the fact that the angle of incidence of the sun rays varies in the case of direct Sun.

Regarding to sidewalk temperature, Italian cypress with height >5 m cast a narrow shadow and therefore a minimal effect on sidewalk temperature was detected, registering 28 °C at shade, while the two individuals with sizes <3 m had lower temperature record but were in combination with another species. A similar result was found with Florida royal palms. Although Florida royal palms have crowns with a wide surface (6.57 m^2), shadow projection is scarce due to the leave shape. The Chinese privet was expected to reduce sidewalk temperatures since crown is globose and has evergreen leaves, but the measured individuals were short and had a sparse crown. Benjamina fig associated with sidewalk temperatures above 30 °C showed crowns with excessive pruning (Figure 2.6). Species such as benjamina fig, bougainvillea, country almond, lemon, yellow bells, flamboyant, moringa and nance concentrated their height between 2 and 5 m and sidewalk surface temperatures between 20 and 27 °C. The use of remote sensing and *in situ* measurements of the LST analysis were used at urban parks and neighborhoods in Puebla, where benjamina fig trees were present (Gomez-Martinez et al., 2021), finding that the sites with benjamina figs were “cooler than average”. Air temperature in plots with different tree coverages and species found that benjamina figs of <20 m height had air temperatures between 16 to 18 °C (Gomez-Martinez et al., 2021; Colunga et al., 2015).

Figure 2.6 Benjamina figs trees with excessive topping located on Sepia Street.

Sixty percent of the sidewalk temperature records above 25 °C were associated with trees located to the east of the house façade, the ones that receive the sun throughout the morning and early afternoon. On the other hand, 69% of shaded sidewalk showed lower temperatures (below 25 °C) and were associated with individuals located to the west of the dwelling. The temperatures recorded on the wall showed the same trend (Figure 2.7). The trees placed on the west side of houses are considered the most efficient for energy consumption saving (Hwuang et al., 2016; Hwang et al., 2015; Berry et al., 2013; Donovan & Butry, 2009; EPA, 2008; Akbari et al., 1997).

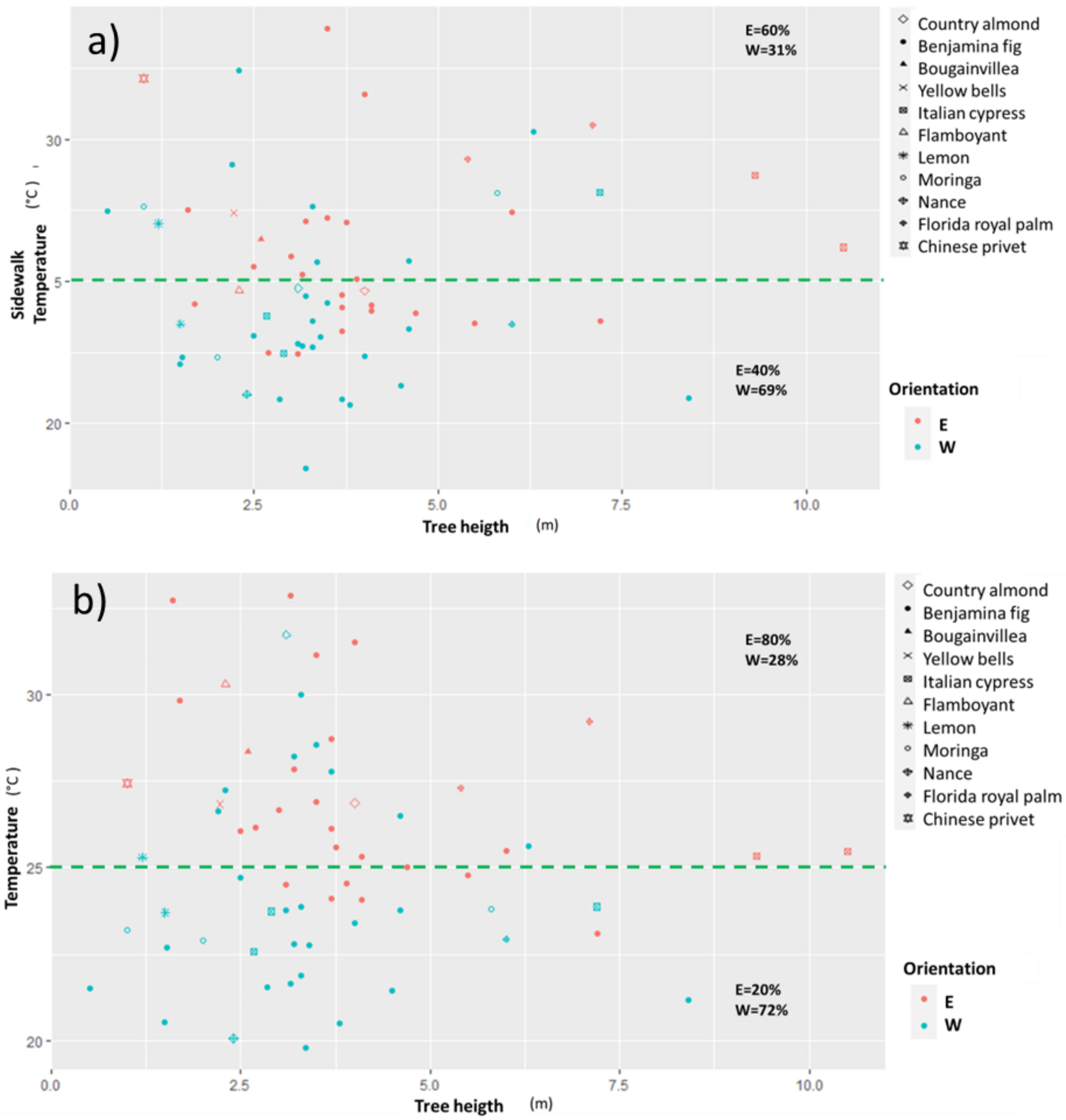


Figure 2.7 Relation of the height and location of the tree with the temperature a) of the sidewalk and b) of the wall that receives shade.

In contrast to the sidewalk temperature, the temperature recorded on the wall seemed to be influenced by the wall color. The 62% of the temperatures measured on white walls with the effect of tree shade recorded values below 25 °C, while 69% of white walls with direct sunlight recorded temperatures between

25 °C and 30 °C (Figure 2.8b) demonstrating that light color, like white, mitigate temperature even in sunlight direct conditions.

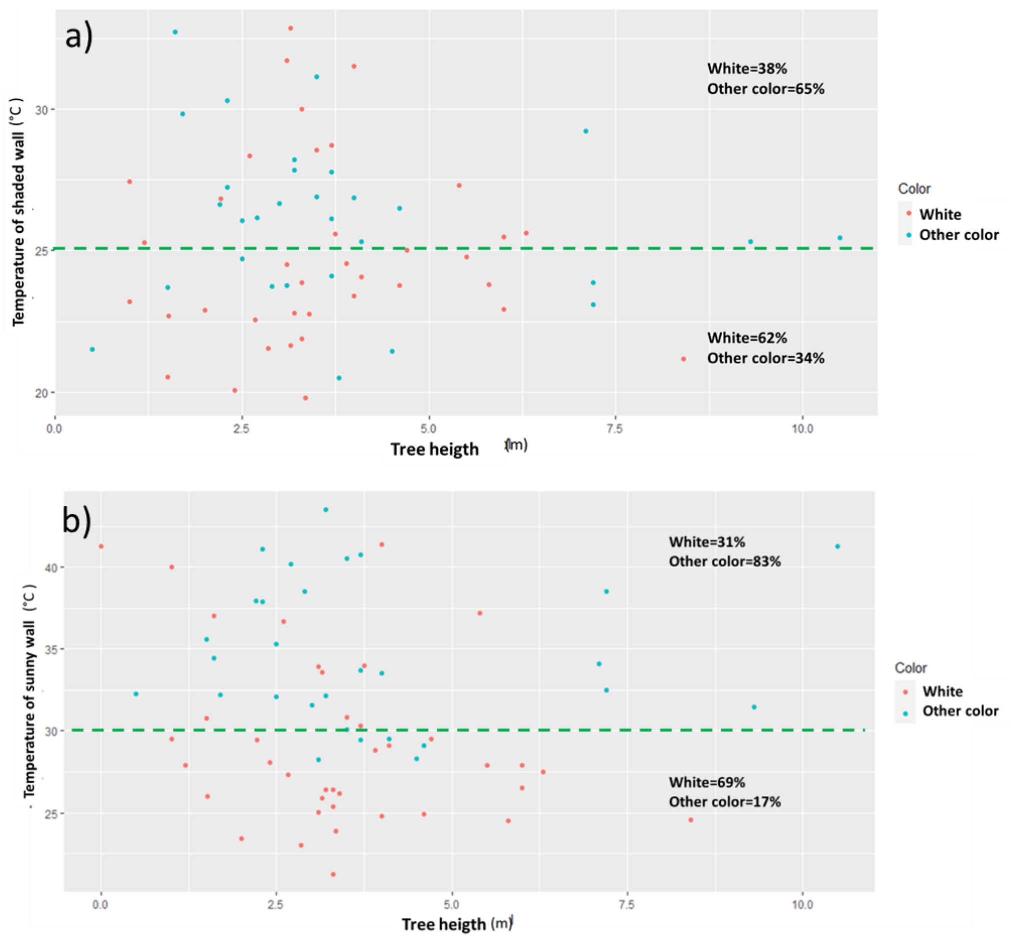


Figure 2.8 Relation of the height of the tree with white/other color wall temperature under a) shaded and b) direct sunlight conditions.

Three distinctive cases were analyzed with air temperature thermometers: house receiving direct sunlight (DS), house shaded (S) and house very shaded (VS) (Table 2.5).

Table 2.5 Interior house temperature and exterior air temperature descriptive statistics in tree shaded and non-tree shaded houses.

Statistical	DS		S		VS	
	Interior	**Exterior**	**Interior**	**Exterior**	**Interior**	**Exterior**
Mode	26.24	24.05	25.82	25.01	24.21	25.07
Median	26.78	26.05	26.00	26.01	24.45	25.02
Mean	26.92	29.06	25.96	25.63	24.71	25.07
Std. Des.	2.56	7.58	1.44	1.48	1.45	2.11
Variance	6.55	57.52	2.07	2.19	2.11	4.44
Maximum	33.79	52.02	30.25	30.02	28.75	30.06
Minimum	21.68	19.05	22.25	22.03	22.25	21.07
Range	12.11	32.97	8.00	7.99	6.50	8.99

The S and VS cases registered more stable temperatures with less than 2 °C variation between interior and exterior environments, while DS registered more than 10 °C of difference, suggesting tree shade prevents extreme changes of air temperature (Figure 2.9).

The hottest mean exterior temperature occurred earlier in the morning for DS case (9:00 to 11:00 h), while for S and VS was between 14:00 to 16:00 h. In comparison, mean exterior maximum temperature for DS and S occurred during the same period during the day (14:00 to 16:00 h) while for VS happened later, from 16:00 to 18:00 h (Figure 2.9).

The heat flux from the exterior and the occupancy habits of lights and electric appliances use contribute to the interior heating of dwellings (Zhang & Calautit, 2022; Dong et al., 2015). In the case of DS and S the interior temperature was never greater than exterior, but for VS from 3:00 to 9:00 h, interior mean temperature overcame exterior temperature. The reason may be a combination of the occupation habits and the exterior condition of shade, since it is the case that received less sunlight during early hours. Nevertheless, more research is needed to determine the causes of this behavior.

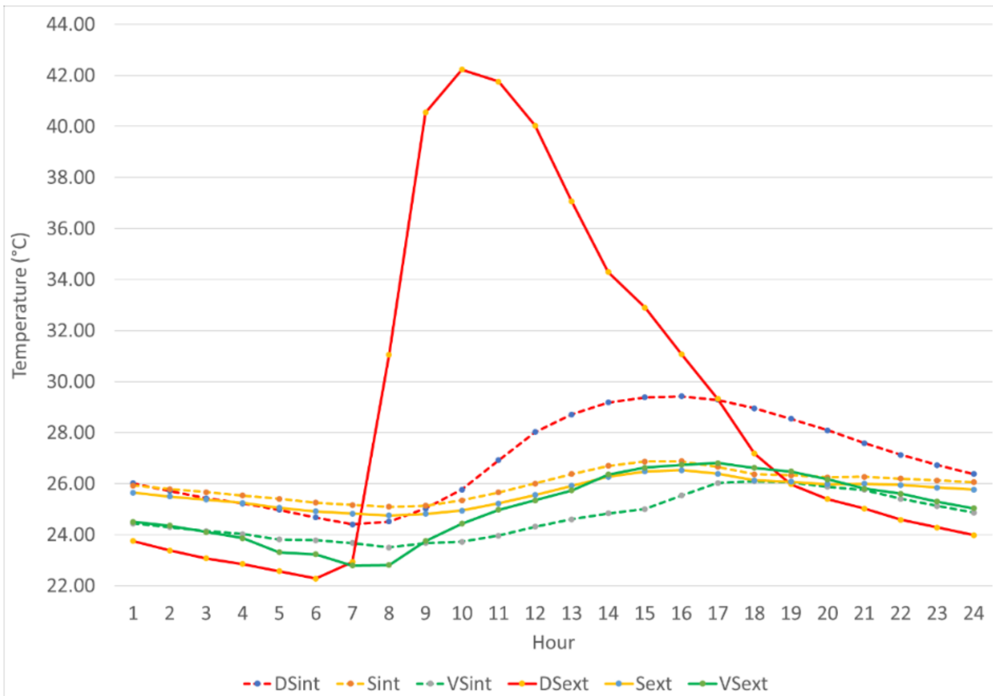


Figure 2.9 Average interior and exterior air temperature of houses with the influence of tree shade and direct sunlight. DSint = direct sunlight interior air temperature, Sint = shaded interior air temperature, VSint = very shaded interior air temperature, DSext = direct sunlight exterior air temperature, Sext = shaded exterior air temperature, VSext = very shaded exterior air temperature.

Mean and maximum temperatures of the three cases of shade were compared (Table 2.6). The VS case had exterior and interior temperature differences with DS greater than 2 °C, but can reached 21.96 °C depending on the hour. The mean interior and exterior temperature of VS differed 1.25 °C and 0.56 °C, respectively, with S case. This result suggests that the gain of thermal temperature mitigation between VS and S condition is least.

Table 2.6 Difference of mean and maximum temperature of very shaded (VS) versus direct sunlight (DS) and shaded (S) houses.

	DS		S	
	Interior	**Exterior**	**Interior**	**Exterior**
Mean	-2.21	-3.99	-1.25	-0.56
Maximum	-5.04	-21.96	-1.50	0.04

Comparing the mean exterior surface and air temperature of the wall, the DS case is the hottest and more extreme since there is 15 °C difference between surface and air temperature, while S and VS temperatures differ less than 2 °C (Table 2.7). Mildrexler et *al.*, (2011) reported similar temperature differentials to the ones found in this study, when he combined MODIS and meteorological data.

Table 2.7 Mean outdoor wall surface temperature, air temperature and temperature differences for the three house conditions analyzed (direct sunlight (DS), shaded (S) versus very shaded (VS)).

	Surface temperature Outdoor wall (°C)			Air temperature Outdoor wall (°C)			Difference between surface and air temperature (°C)		
	DS	**S**	**VS**	**DS**	**S**	**VS**	**DS**	**S**	**VS**
Mean	44.06	26.67	26.83	29.06	25.63	25.07	15.00	1.03	1.76

2.7 CONCLUSIONS

Tree shade can reduce both, atmospheric and surface temperatures. Tree shade reduced the surface sidewalk and exterior wall temperature of 26.5 °C and 6 °C, respectively. In the case of air temperatures, tree shade reduced temperature next to an exterior wall by 3.43 to 3.99 °C and reduced temperature next to an interior wall by 0.96 to 1.25 °C.

Tree cover obstruction of direct sunlight on houses relates to a more stable air temperature environments (outdoor and indoor) with a thermal oscillation of less than 2 °C in the hottest hours of day.

The shade quality (crown and shape), orientation of the tree related to the house, and exterior wall paint color also influenced the cooling effect of trees.

A recommendation for dwellings to reduced exterior and interior temperature is to plant trees with globose crown shape at the east side of the house and paint exterior walls with white or clear colors. This help to mitigate the maximum thermal hours. In general, the thermal mitigation effect is appreciable when trees are 2.5 m tall and are located at 5 m distance from houses.

To broad the understanding of house indoor comfort temperature it is necessary to include the effect of humidity and wind inside and outside houses and to increase thermal indoor data.

CHAPTER III. HOW MUCH DOES THE URBAN TREE SHADE HELP IN SAVING ELECTRICITY CONSUMPTION IN DWELLINGS OF MONTERREAL NEIGHBORHOOD OF TUXTLA GUTIERREZ CITY, CHIAPAS?

3.1 ABSTRACT

One of the resources with the greatest demand in the urban areas and with serious environmental consequences for its generation, is electrical energy. This resource is essential for the well-being of the population, as in the case of tropical cities in Mexico, for example, Tuxtla Gutiérrez (TGZ), capital of the state of Chiapas, the demand for electricity is strongly focused on cooling homes and an increase of 219% is expected for the year 2030 in the context of the Urban Heat Island and Climate Change.

There are various strategies proposed to regulate the temperature in homes and cities. The use of air conditioning is the most popular house cooling system, however, its energy demand is high, as well as its environmental ones. At the opposite extreme are trees that have shown good results as temperature regulators, both indoors and outdoors.

The objective of this research is to provide economic elements that support the benefits of urban trees, quantifying the service it provides as a buffer against extreme temperatures through the shade it generates. For this, surveys were carried out in the Monterreal neighborhood of the city of Tuxtla Gutiérrez, in order to know the habits of use of electrical appliances and their characteristics. With the information collected, the energy consumption of each household surveyed, and the associated cost were calculated, making a comparison between those houses that received a tree shade and those that did not.

Finally, it was estimated that the consumption of electricity per capita (CE_{pc}) is reduced by 32% when the house is shaded by trees, discovering an average saving of 43% in the annual cost, which means an annual saving between $300 and $900 Mexican pesos.

3.2 RESUMEN

Uno de los recursos con mayor demanda en el entorno urbano y con serias implicaciones ambientales para su generación, es la energía eléctrica. Este recurso resulta indispensable para el bienestar de la población, como en el caso de ciudades tropicales de México, por ejemplo, Tuxtla Gutiérrez (TGZ), capital del estado de Chiapas, donde la demanda de energía eléctrica está fuertemente dirigida al enfriamiento de los hogares y se prevé un incremento de 219% para el año 2030 en el contexto de la Isla de Calor Urbana y el Cambio Climático.

Son diversas las estrategias propuestas para regular la temperatura en viviendas y ciudades. El uso de aire acondicionado es el sistema de enfriamiento de hogares más popular, sin embargo, su demanda energética es alta, así como sus implicaciones ambientales. En el extremo opuesto se tiene a los árboles que han mostrado buenos resultados como reguladores de temperatura, tanto en ambientes externos como interiores.

El objetivo de esta investigación es aportar elementos económicos que sustenten los beneficios del arbolado urbano cuantificando el servicio que presta como amortiguador de temperaturas extremas a través de la sombra que genera. Para ello se realizaron encuestas en la colonia Monterreal de la ciudad de Tuxtla Gutiérrez, con el fin de conocer los hábitos de uso de los aparatos eléctricos y sus características. Con la información recopilada se calculó el consumo energético de cada hogar encuestado y el costo asociado, haciendo una comparación entre aquellas viviendas que recibían sombra de árbol de las que no.

Finalmente se estimó que el consumo de electricidad *per capita* (CE_{pc}) se reduce en 32% cuando la vivienda recibe sombra de árboles, generando un ahorro promedio del 43% en el costo anual, lo que significa un ahorro anual entre $300 y $900 pesos mexicanos.

3.3 INTRODUCTION

By the year 2020, 79% of the Mexican population lived in cities (INEGI, 2022), mostly of small and medium size (100 thousand to 1 million inhabitants) which had the highest population increase with an average annual growth of 1.5% in the last decade (INEGI, 2022). These tendencies suggest the formation of new urban centers throughout the country, with urbanization processes that require planning in order to guarantee the well-being of the inhabitants in the medium and long term.

Although it is a social phenomenon in our country what drives the growth of the urban sprawl (Gutiérrez, 2003; Unikel, 1968), its environmental implications are usually irreversible (UN, 2019; Revi et al., 2014; Satterhwaite, 2009). In fact, to guarantee the social wellbeing of the urban population in the face of current environmental phenomena, such as Climate Change (CC) and the Urban Heat Island (UHI), requires citizen participation (Andrews et al., 2008), the implementation of mitigation strategies (Silva & Golden, 2012; Stone et al., 2012; Rizwan et al., 2008), the supply of basic resources, sustainable economic development, control of population growth and environment protection (Mika et al., 2019; Wang, 2018; Xue et al., 2014).

One of the resources with the greatest demand in cities is electrical energy, however, its production in Mexico causes a lot of pollution. The 69% of the country's electricity is generated from the burning of fossil fuels (Vijay et al., 2004), emitting 10 million tons of CO_2 in 2015 (McNeil et al., 2018). Considering that Mexican dwellings are the second largest consumer of electricity at the national level (Escoto & Sánchez, 2017; Murillo-Rodríguez et al., 2015), and adding to the effects of CC, UHI (Akhmat et al., 2014) and the country's urbanization trend, it is estimated that the production of greenhouse gases derived from electricity production will reach 20 million tons by 2030 (Tejeda et al., 2022; McNeil et al., 2018).

Mc Neil et al. (2018) mentioned for Mexico that, of the total electrical energy consumed in houses during the year 2015, approximately 9% was used for cooling. Besides, the demand will increase six times more by the year 2050 due to the effect of the increase in temperature and accessibility to air conditioning equipment. This has serious environmental and economic implications, not only for the end user, but also for the government, since by 2015, 50% of electricity production was subsidized.

Cities in tropical zones will suffer even more the increase in temperature (Tejeda et al., 2022; García-Cueto et al., 2009; Tejeda & Rivas, 2003) compared to temperate zones. This trend has been observed since 2001 when the average consumption of electricity per user declined in temperate climates and increased in hot zones in a sustained manner (de Buen R. & Navarrete B., 2019). An example of this situation is the city of Tuxtla Gutiérrez (TGZ), the economic-political center and capital of the state of Chiapas (Silva et al., 2015). As a tropical city, TGZ temperatures above the national average and heat wave (HW) events are recorded; however, since 2003, the frequency of occurrence of these events has increased, presenting the ten most severe events in the last 11 years (Pascacio, 2021). High temperatures and HW exert strong pressure on city dwellers who seek strategies to minimize their effects. The city suffered a rapid growth in urban sprawl and requirements in the demand for electricity, mainly for house cooling (Tejeda et al., 2022; Silva et al., 2015). In fact, the city consumes 25% of the electricity produced in the state and of 87% out of the total consumption is domestic (ICIPLAM, 2021). Indeed, Tejeda et al. (2022) estimates that the city will increase its energy demand by 219% in the context of UHI and CC by the year 2030.

The main mitigation approach for dealing with the increase in the demand for electricity for cooling, is based on the use of efficient lighting and appliance technologies; however, despite the availability of this type of equipment, the demands of the sector continue to increase (Satterhwaite, 2009). Thanks to technological advances, residential cooling systems are more affordable in cost, as well as compact and efficient (Randazzo et al., 2020; Lester, 2015); however, Randazzo et al., (2020) mentions that once residents start using air conditioning (AC) in their house, the electricity consumption bill (CE) increases between 35 to 42%.

The use of AC is not the only option in house for cooling; there are various CC and UHI mitigation strategies that have been proposed to regulate the temperature in houses and cities, such as: high-albedo paints and waterproofing (Silva & Golden, 2012; Rosenfeld et al., 1995), green roofs (Shafique & Kim, 2017; Vazquez et al., 2016) and windows with tinted glass (Litardo et al., 2020; Rizwan et al., 2008); however, urban trees have shown good results as temperature regulators considering that they are efficient in reducing temperature and at the same time provide additional benefits such as improving air quality, beautifying the landscape and increasing residential capital gains (Bajsanski et al., 2019; Ucar et al., 2018; Colunga et al., 2015; Zhang et al., 2015; EPA, 2008; Rosenfeld et al., 1995).

Despite the benefits that trees bring to the urban environment, it is one of the most punished natural elements because it competes for space affecting sidewalks, pipes and wiring (Camacho-Cervantes et al., 2014). Although tree environmental benefits are recognized, it is still common to remove them when they compete with grey infrastructure (EPA, 2008) and its disadvantages outweigh the benefits that provides.

The aim of this research is to provide economic elements that support the benefits of urban trees by quantifying the service as a buffer against extreme temperatures through shade. For this, surveys were carried out in the Monterreal neighborhood of the city of Tuxtla Gutiérrez, in order to know the habits of use of electrical appliances and their characteristics. With this information, the *per capita* energy consumption was estimated of each household surveyed and the associated cost was calculated based on the rates published by the Federal Electricity Commission (CFE) of Mexico. Finally, the difference in energy consumption and cost between houses with and without tree shade is compared.

3.4 CHARACTERIZATION OF THE STUDY AREA

The city of Tuxtla Gutiérrez is the capital of the state of Chiapas, in the Mexican southeast; the city covers 40% of the municipality and is located between the coordinates 16° 48' 46” N, 93° 13' 12” W and 16° 40' 49” N, 93° 02' 19” W. The altitude ranges from 435 to 917 m and the climate is warm and subhumid with rains in summer. The rainy season runs from May to October, and the average annual rainfall is 951 mm. The average annual temperature is 25.4°C, with the hottest months being April and May with maximums of up to 45.5°C. The city is surrounded by 4.9 km^2 of Natural Protected and Conservation Areas: “Cerro Mactumatzá”, “El Zapotal” Recreational Ecological Center, the “Villa Allende” Forest Zone, and the “Cañón del Sumidero” National Park (ICIPLAM, 2013). These areas have native deciduous forest, while 75% of the urban trees are exotic (Román, 2017) and are distributed mainly in 193 gardens for public use and a country club.

The city has expanded rapidly as it is the main economic and service center of the state. From 2007 to 2018 the area increased from 7.8 km^2 to 107 km^2 (HATG, 2007), an approximate annual increase of 11%. This expansion is mainly caused by urban residential developments with few ecological regulations and therefore the study area is a colony considered a *hot spot* inside the city.

The Monterreal neighborhood is located north of TGZ and has an area of 0.28 km^2. The dwelling development has 967 houses, and the energy consumption rate is 1b, according to Federal Electricity Commission, which is assigned to houses located in areas with an average of 28 ° C during summer and with an average electricity consumption of less than 400 kilowatt-hours per month.

There are three areas of bare soil, a wasteland lot at the beginning of the neighborhood that adjoins Av. Laguitos with an area of 3.1 ha, Parque de Las Serpientes with 0.63 ha and Parque Monterreal with 1.19 ha. These areas have little or no vegetation, which is the reason for accumulating a large amount of heat provided by the Sun during the day and for being considered a *hot spot* (Figure 3.1).

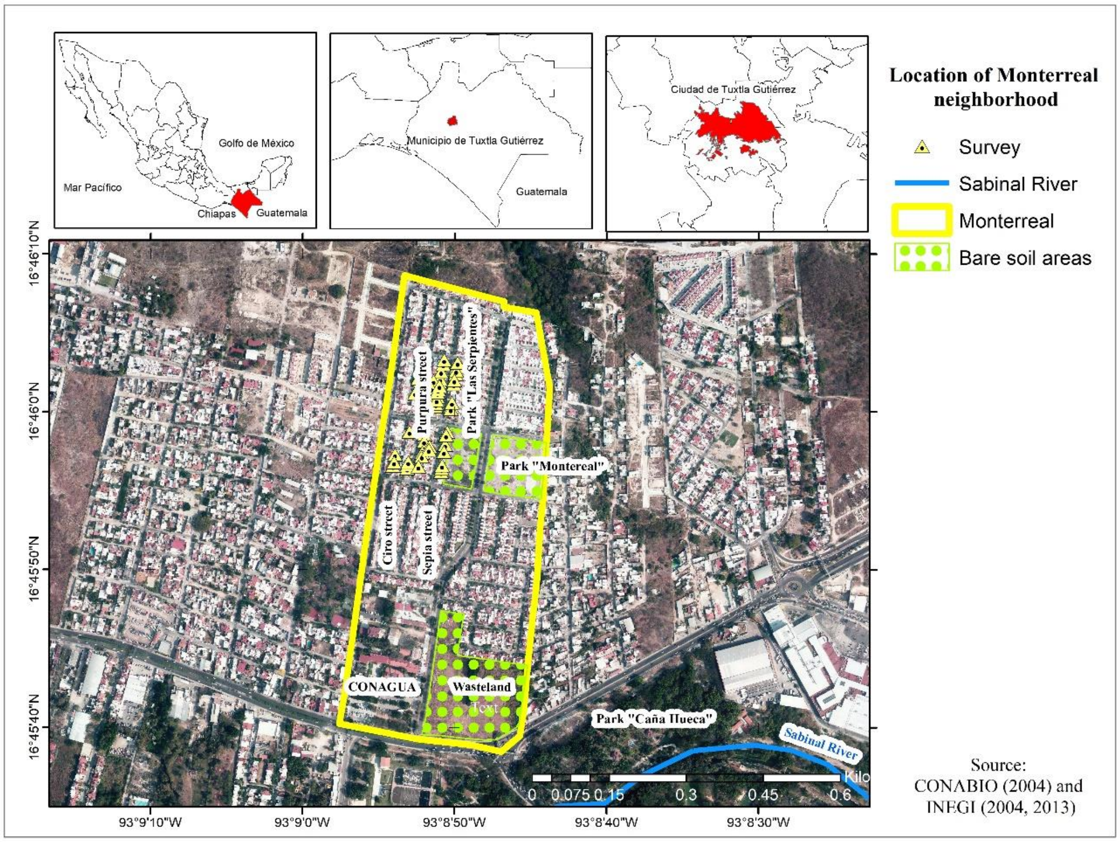


Figure 3.1 Location of the Monterreal neighborhood in the city of Tuxtla Gutiérrez.

3.5 MATERIALS AND METHODS

A methodology was developed to estimate the energy consumption-cost of dwellings that received tree shade versus those who do not (Figure 3.2).

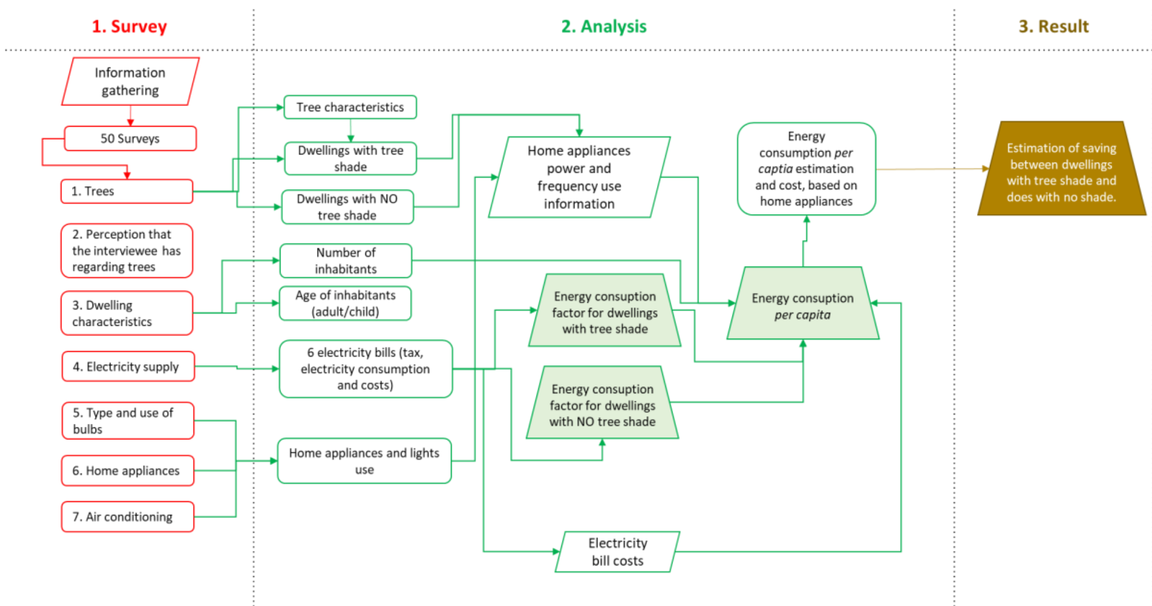


Figure 3.2 Methodology for energy consumption-cost estimation of dwellings that receive tree shade versus those who do not.

During August 2021, surveys were carried out in houses in the Monterreal neighborhood in the city of Tuxtla Gutiérrez, Chiapas, mainly at Sepia, Purpule and Ciro streets. The number of surveys was determined based on equation 3.1.

$$n = \frac{Nz^2pq}{(N-1)E^2+z^2pq} \qquad \textbf{(3.1)}$$

Where n is the sample size to survey, N is the total number of dwellings (967) in the Monterreal neighborhood, E is the level of significance (0.15), z is the statistic power (1.96) and p and q constants (0.5 respectively).

The survey was based on the National Survey on Energy Consumption in Private Houses, ENCEVI (INEGI, 2018), without covering all the topics (Annex 1) and consisted of 48 questions distributed in seven sections: 1. Trees, 2. Perception of the interviewee regarding trees, 3. Characteristics of the dwellings, 4. Electricity supply, 5. Type and use of light bulbs, 6. Electrical appliances, and 7. Air conditioning.

The sections on type and use of light bulbs, electrical appliances, and air conditioning collect information on the number, type and frequency of use in daily hours of each appliance.

The electricity supply section considers the electrical consumption record (EC), as well as the bimonthly or monthly associated cost according to the bill from the Federal Electricity Commission for each household; however, 90% of those interviewed did not have the information (electricity bill) at the time of conducting the survey and only provided verbal information of the last payment.

Only six dwellers provided historical CE information between 2019 and 2022. With the information of electricity bills from these six dwellers, were generated six different correction factors (Murillo-Rodríguez et al., 2015). These correction factors (B_i) were used to adjust the calculated electricity consumption based on the appliances of those surveyed houses that did not provide electricity bill information. The correction factor methodology is described forward.

The electrical consumption can be calculated according to equation 3.2 by multiplying the power by the time of use:

$$Electric\ consumption\ (W \cdot h) = Power\ (W) \cdot Time\ (h) \qquad \textbf{(3.2)}$$

The time variable is determined based on the survey and data collection; however, the power varies according to the trademark, year and model of the equipment. Such information was not enough recorded in the survey carried out, and was complemented bibliographically (Escoto & Sánchez, 2017, 2019; Oropeza & Petzold, 2018; Gargallo, 2017; Murillo-Rodríguez et al., 2015; Morales & Luyando, 2014).

To determine the total consumption of the surveys that did not have an electricity bill, the appliances were grouped into classes of final use, such as appliances for: entertainment, to stabilize the temperature, for washing, for cooking and miscellaneous. The consumption of each class was estimated to finally add them and obtain the total electrical consumption according to equation 3.3 (Escoto & Sánchez, 2019).

$$C_t = (\sum_1^n Class_1 + \sum_1^n Class_2 + \sum_1^n Class_3 + \sum_1^n Class_4 + \sum_1^n Class_5) * B_i \quad \textbf{(3.3)}$$

Where Ct is the total consumption, n the elements of each class, and B_i is correction factor for the *i-th* group according to the characteristics of tree shade, tree height, presences of air conditioning, number of appliances and number of inhabitants.

The correction factors (B_i) were the result of dividing the estimated EC based on the appliances, according to equation 3.2, by the EC reported at the electricity bill available of the six houses, as the equation 3.4. Since each house have different characteristics of tree shade, tree height, presences of air conditioning, number of appliances and number of inhabitants, the correction factors were used in accordance with those features.

$$B_i = \frac{C_{ti}}{EC_i} \quad \textbf{(3.4)}$$

Where B_i is the correction factor according to house characteristics of tree shade, tree height, presences of air conditioning, number of appliances and number of inhabitants. C_{ti} is the total energy consumption based on house appliances and EC_i is the energy consumption based on the electricity bill.

Once the EC was adjusted with the previously described correction factors, it was divided into de number of inhabitants getting EC *per capita* (EC_{pc}). Finally, when obtaining the consumption per class, the cost of the (EC_{pc}) was estimated with equation 3.4 based on the cost reported in the six electric consumption bills.

Once the consumption and cost of each household were calculated, the results of the houses that received tree shade were compared to those that did not.

Finally, the average difference between both groups were considered as an estimator of energy savings in houses that receive tree shade.

3.6 RESULTS AND DISCUSSION

Following equation 4.1, the sample size for the survey was identified as 41 surveys, however we raised such number of 51, of which 28 had tree shade influence and 23 did not.

As formerly mentioned, the first part of the survey describes the trees in terms of location with respect to the house, distance to it, species, height, and perception. On this regard, of the total dwellings surveyed, 55% had influence of tree shade, fourteen trees were located at the east of the house, and fourteen to the west, at an average of 2 m distance. Table 3.1 shows the characteristics of the trees that influenced those houses.

Table 3.1 Urban trees that shade surveyed dwellings.

Family	Common name	Species	Number of trees	Mean height (m)
Cupresaceae	Italian cypress	*Cupressus sempervirens* L.	1	11
Moraceae	Benjamina fig	*Ficus benjamina* L.	24	4
Moringaceae	Moringa	*Moringa oleifera* Lam.	1	1
Nyctaginaceae	Bougainvillea	*Bougainvillea attractiveness* Willd.	1	4
Rutaceae	Lemon	*Citrus aurantifolia* (Christ) Swingle	1	2

The population surveyed indicate that one of the main benefits of urban trees is to reduce temperature (44%) as well as improve air quality (42%). These results are in line with the findings of various studies that had reported that increasing the area of urban trees decreases the ambient and surface temperature to a greater extent, compared to other CC and UHI mitigation strategies (Cortes et al., 2022; Zheng et al., 2022; EPA, 2008).

Only 5% of the surveyed individuals recognized that trees regulate water runoff, a low percentage despite the fact that the city had suffered floods on several occasions (SPCM, 2010, 2015). Only 4% considered trees as an aesthetic beautifier element of the landscape (Figure 3.3).

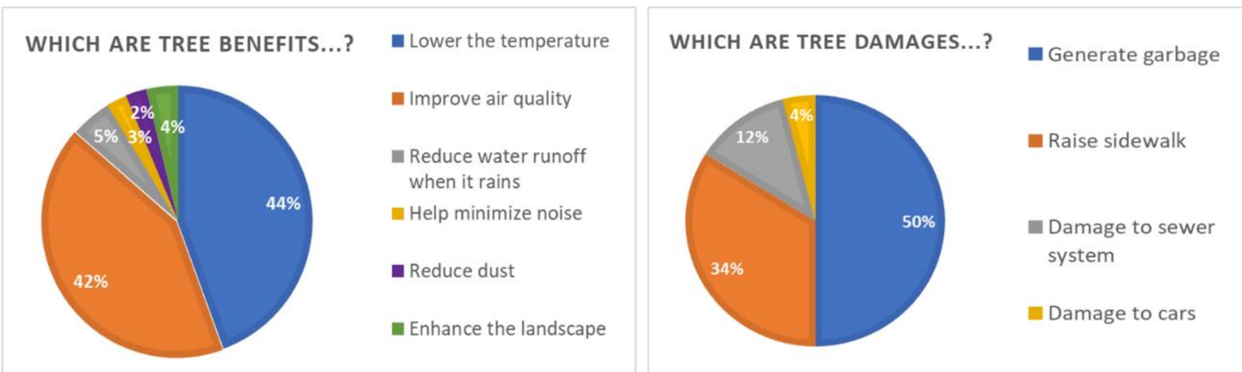


Figure 3.3 Perception of surveyed population about tree benefits and damages.

Despite recognizing important tree benefits, only 10% of the surveyed population has participated in any reforestation activity. It is necessary to expand the survey to understand why the population is scarcely involved with conservation activities. Understanding if the reason is for apathy, lack of information or time, results will help to establish strategies that allow raising awareness more efficiently on the subject.

The 50 % of surveyed dwellers considered that trees generate garbage (foliage) and only 17% use the leaves to make compost. Additionally, they complained about tree roots damaging sidewalks (34%) and pipes (12%). These damages are related to the Benjamina fig since its root system is highly invasive, (Vargas-Garzón & Molina-Prieto, 2012) causing problems in the infrastructure. In fact, Benjamina fig is the most replaced or felled tree by the inhabitants of the colony.

The negative perception of the trees reflected in the survey is biased by the growth habit of this species. This is an example of the importance of correctly choosing the species to be used as urban trees.

The EC is determined by social, environmental and construction factors. Regarding the characteristics of the house, only 12% of those surveyed had made some modification to their house, with an extra room being the most common. The average surface of the house is between 151 and 180 m^2, with three bedrooms, a living room, a dining room, a kitchen, a study room and a backyard. They were built of solid brick, with a mosaic floor and a concrete ceiling. In general, it can be assumed that the households surveyed have the same construction model.

The 54% of dwellers had applied red waterproofing paint as roof coating, 31% white waterproofing, 4% had not applied coating, 2% covered the roof with mosaic and 9% did not know. The main use of waterproofing is as a coating to prevent roof leaks (Sharkawi & Baharun, 2016) and few respondents recognized its additional function as a temperature mitigator. As mentioned by Sharkawi et al., (2016) reflective coatings can reduce the air temperature of a room by up to 1.9 °C.

It is important mentioning that, regarding environmental factors, only the presence of trees that provide shade was considered. Meteorological variables that affect ambient temperature, such as relative humidity and wind, were not explored in this research.

The social factors that influence the EC are (1) the number of inhabitants, (2) habit of using electrical appliances and lights, (3) the hours of occupation of the house, the age of dwellings and average income, which have a directly proportional relationship with the electricity consumption (Sánchez, 2012). In this work only social factors (1) and (2) were considered as a variable. Factor (3) average income was assumed constant, i.e. that the inhabitants within the neighborhood shared the same socioeconomic stratum and the age differed only if there were children or adults in the household. The habit of use was complemented with information reported by the CFE (CFE, 2015) and Cruz & Durán (2015). Regarding the hours of occupancy, as the study was carried out during the COVID-19 quarantine, so the reported values were unusually higher (24 hours), which could overestimate the final calculation of the EC.

On average, each household surveyed had 14 appliances (Table 3.2), which is below the national average (18 appliances) according to Cruz & Durán (2015). All houses have a refrigerator, stove, blender and television, although 72% have more than one television.

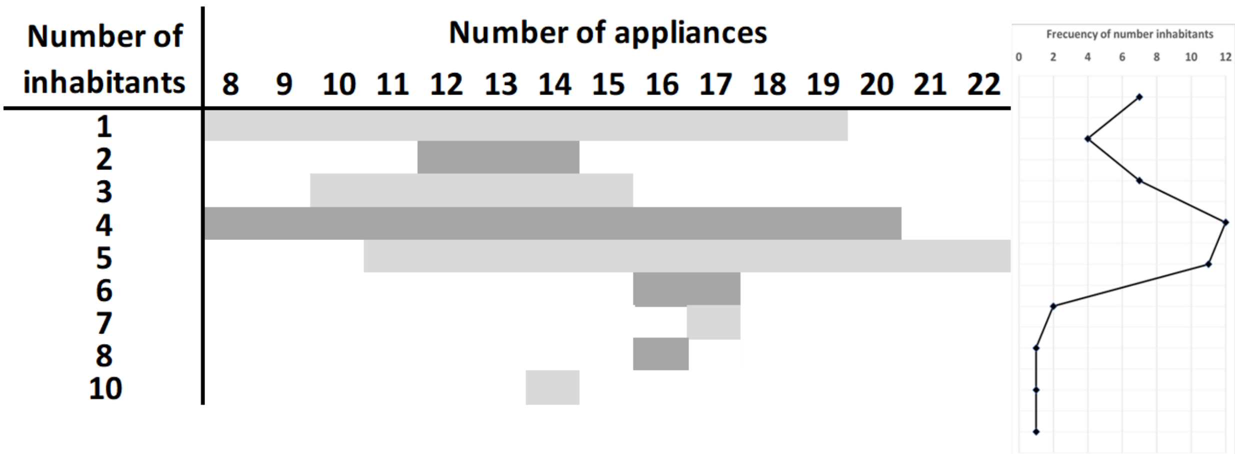
Table 3.2 Appliance presence at surveyed dwellings.

Appliance	Home presence	Appliance	Home presence
Microwave	94%	**TV**	100%
Blender	100%	**Refrigerator**	100%
Mixer	61%	**Ceiling fan**	71%
Coffee maker	73%	**Foot fan**	63%
Roaster	27%	**Tower fan**	4%
Electric oven	20%	**Videogame console**	12%
Hair dryer	22%	**Washing machine**	82%
Hair iron	14%	**Stove**	37%
Dryer	20%	**Air conditioning**	53%

Table 3.3 shows the average number of appliances reported in the survey according to the number of inhabitants in each house. Those households with

one, four and five members occupy the largest number of appliances reported in the surveys, coinciding with the most frequent number of members per household. In strata with more than five inhabitants, the number of appliances is drastically reduced, possibly because of economic factors.

Table 3.3 Appliance presence at surveyed dwellings and number of inhabitants.



All households surveyed had some system to cool their house, either fans (63 to 71%) or AC (53%); and about 71% combined both systems (Figure 4.4). This proportion contrasts with the national data reported by Cruz & Durán (2015) where only 12.37% of sample dwellings had air conditioning equipment and 45% used fans (INEGI, 2018). In tropical climates like in TGZ, the cooling of houses is essential along the year implying a cost in the consumption of electricity. Oropeza & Petzold, (2018) estimated that approximately 21% of the EC consumed by a house is used for cooling; however, when there is an AC system, consumption rises to 44%. The number of households that combine both systems is unknown.

It was noted that as the number of AC systems in a house increased the number of any type of fan decreased (Figure 3.4). Therefore, there is a tendency to replace fans with AC and this will have future implications in the demand for the service that the CFE must consider.

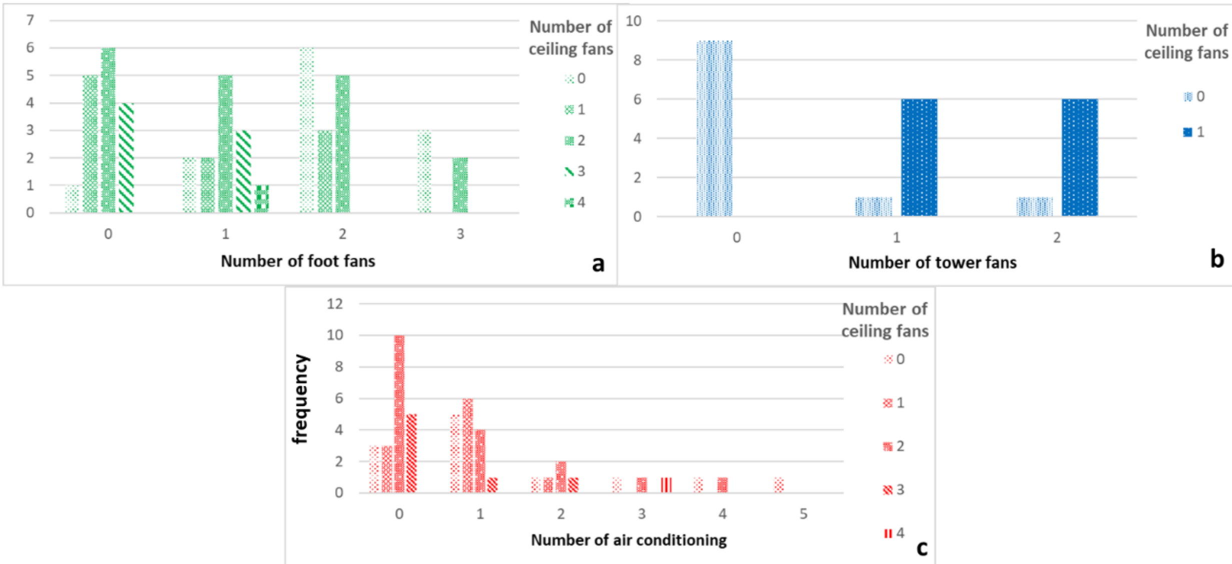


Figure 3.4 Number of a) foot fans, b) tower fans and c) air conditioning systems according to the number of ceiling fans reported in surveys.

In addition to the number of appliances, usage habits are also important to define the magnitude of electricity consumption, which can be seen in table 3.4 and the correction factors at table 3.5.

Regarding the number of inhabitants per dwelling, the average is three adults and one child (4). In 53% of the surveyed dwellings 4 to 5 people lived and 1 to 2 people in the 24%. These data are similar to the national data reported by Oropeza & Petzold (2018) and Pérez (2019). EC_{pc} is significantly reduced as the number of residents increased as the use of appliances is shared with the inhabitants (Tejeda et al., 2022; Pérez, 2019; Sánchez, 2012), which is consistent with the data surveyed; for example, houses inhabited by a single person or couples without children are the ones that consume the most energy *per capita* (Figure 3.5).

Table 3.4 Appliances power electricity and time of use.

Appliance	Power (Watt)	Time of use (minute, hour)
Microwave	1200	15 min/day
Blender	400	10 min/day
Mixer	200	1 h/ 2 times per week
Coffee maker	750	1 h/day
Roaster	1000	10 min/day
Electric oven	1000	15 min/day
Hair dryer	1600	10 min/day
Hair iron	150	10 min/day
Dryer	5600	4 h/2 times per week
Refrigerator	375	12 h/day
Small TV	120	6 h/day
Medium TV	250	6 h/day
Big TV	360	6 h/day
Ceiling fan	65	8 h/day
Foot fan	125	8 h/day
Tower fan	71	9 h/day
Videogame console	250	4 h/day

Appliance	Power (Watt)	Time of use (minute, hour)
Washing machine	400	5 h /2 times per week
Stove	4.1	5 min/day
Air conditioning (1 ton)	1160	8 h/day
Air conditioning (2 ton)	2280	8 h/day
Focus (8 of 15 Watts)	120	6 h/day
Focus (8 of 60 Watts)	480	6 h/day

Table 3.5 Correction factors for electricity consumption.

Correction factor	Description
0.8936	Without tree presence or tree less than 3m heigth, with air conditioning, more than 10 electronic appliances and more than 4 inhabitants.
0.5039	Without tree presence or tree less than 3m heigth, with no air conditioning, less than 10 electronic appliances and less or 4 inhabitants.
0.5888	Without tree presence or tree less than 3m heigth, with no air conditioning, less than 10 electronic appliances and more than 4 inhabitants.
0.4671	Trees with more than 3 m heigth, with air conditioning, more than 10 electronic appliances and more than 4 inhabitants.
0.2858	Trees with more than 3 m heigth, with no air conditioning, more than 10 electronic appliances and more than 4 inhabitants.
0.1364	Trees with more than 3 m heigth, with no air conditioning, less than 10 electronic appliances and less or 4 inhabitants.

Despite the fact that previous research reported a directly proportional relation between age and energy consumption, this was not perceived in the present analysis (Figure 3.5).

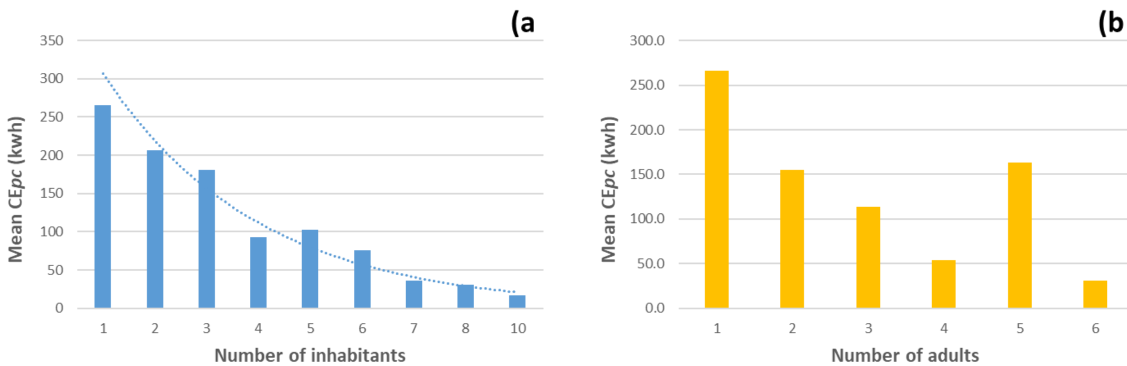


Figure 3.5 Energy consumption *per capita* (kwh) per a) number of inhabitants and b) number of adults.

The monthly mean EC_{pc} of dwellings without the influence of tree shade was 1.5 times greater than that of houses that received tree shade (Table 4.6) and the reduction of electricity consumption was 32%. These values are lower than those mentioned by other authors who report electricity consumption of 2 and 2.6 times higher in houses that received direct light (Pandit & Laband, 2010) and a reduction in electricity consumption of 35% to 50% in houses with tree shade (Adedoyin et al., 2014; Pandit & Laband, 2010; Donovan & Butry, 2009; Akbari et al., 1997). The variation will be caused by two reasons: First, the CFE had been gradually updating the electricity meters since 2021, therefore, the consumption of those houses with electricity bill information registered by modern electricity meters may be more accurate, but older electricity meters were more common in surveyed houses. Second, the information used for table 3.6 are de 51 surveyed houses, where just six provided electricity bill information and the rest estimated the consumption based on electric appliances amended with the correction factors. This may cause an underestimation of EC_{pc}.

Table 3.6 Mean monthly per capita electricity consumption (ECpc) of surveyed dwellings.

	Monthly (kwh)
EC_{pc} with tree shade	64
EC_{pc} with no tree shade	95

The seasonal estimation of energy consumption was based only on the electricity bills information shared by six surveyed houses. Spring is the season with the highest EC_{pc} (Table 3.7). According with what was reported by Castro-Mendoza et al. (2022), the months with the highest thermal intensity are April and May and, therefore, with the highest EC. The EC_{pc} of the dwellings that did not receive tree shade consumed 2 to 2.6 more energy than those receiving shade, like Pandit & Laband (2010) mentioned. This suggested that the estimations made for surveyed dwellings with no energy bills information were underestimated and that consumption in houses is much higher.

Table 3.7 Mean *per capita* electricity consumption (CE_{pc}) per season of the year of surveyed dwellings with electricity bill information.

	Energy consumption *per capita* (kwh)	
Season	**Tree shaded**	**No tree shaded**
Spring	112	231
Summer	101	247
Autum	82	217
Winter	86	206

Considering that all the households surveyed have the same rate (1b) for electricity consumption, with the information available from the receipt of the six dwellings, equation 3.3 was fitted to estimate the cost of electricity consumption for the rest of the houses surveyed (Figure 3.6).

$$y = -0.0042x^2 + 3.0174x - 67.782 \qquad \textbf{(3.3)}$$

Where y is the cost ($) estimated of the mean monthly electricity consumption (x) per person.

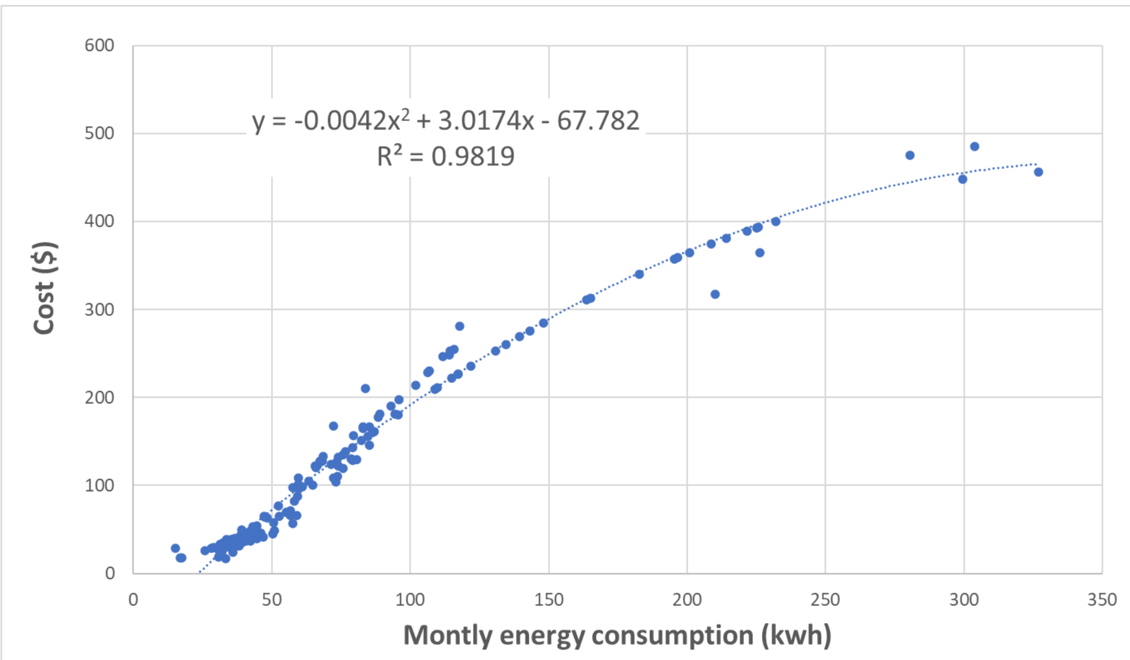


Figure 3.6 Mean energy consumption per month (kwh) and cost ($) relation.

The cost of EC*pc* of dwellings that did not receive tree shade was 1.7 higher compared with to those shaded (Table 4.8), finding an average saving of approximately 43% in the cost of electricity use in houses that receive tree shade.

Table 3.8 Comparison of monthly mean *per capita* cost ($) of surveyed dwellings according to their tree shaded condition.

	Monthly mean *per capita* cost ($)
Tree shaded house	93
No tree shaded house	164

When households were grouped in those that used AC and those that did not, it was observed that the increase in both electricity consumption and the associated cost was greater (50 to 70%) in households that use AC (Table 3.9). This result is higher than that reported by Randazzo et al., (2020), who mentioned an increase of 35 to 42% in electricity consumption; however, his research focused on eight cities in temperate countries such as Norway, Canada, France and Japan, which do not reach the temperatures of the city of TGZ, as it has a tropical climate.

Table 3.9 Comparison of *per capita* electricity consumption and mean monthly cost between shaded and no shaded dwellings.

	Tree shaded		No tree shaded	
	AC	**No AC**	**AC**	**No AC**
Ec_{pc} (kwh)*	182	56	196	98
Mean montly cost of Ec_{pc} (MXN)	314	83	320	158

*EC*pc*= Electricity consumption *per capita*

3.7 CONCLUSIONS

Tree shade reduced 32% *per capita* of energy consumption and 43% in *per capita* annual cost, which means an annual *per capita* saving between $300 to $900 Mexican pesos. Considering that data suggests an underestimation of electricity consumption, it is possible that the annual saving will be greater, but it will be necessary to improve the correction factors for a better estimation.

Various factors increased electricity consumption. AC raised electrical consumption and therefore the associated cost by 50 to 70%; it was the appliance that most affects electricity consumption in the surveyed dwellings. The second factor of importance was the number of people living in the house and it maintained an inversely proportional relation with electricity consumption.

Even when, correction factors were considered depending on the specification of tree shade, tree height, use of air conditioning, number of appliances and number of inhabitants of each house, it is recommended to increase the survey to get more specific information of time of use, power of each appliance, and age of inhabitants.

OVERALL CONCLUSIONS

This work evaluated the performance of tree as a mitigator element of extreme temperatures in the city of Tuxtla Gutiérrez (TGZ) from different approaches and spatial scales.

In the first part the land surface temperature (LST) of the city were scanned to recognize the hottest places during the time of the year with the highest temperatures (spring). The combination of techniques used allowed spatially and temporally locating the evolution of the UHI within TGZ, as well as the evolution in the change of land use and cover that intensified the daytime LST within the city.

Although metal roofs were the hottest surface during the day (>40 °C), they occupied less than 3% of the total area of the city and correspond mainly to shopping centers or parking lots. Its contribution to the ambient temperature of TGZ is minimal, compared to the BAS coverage, which occupied 11% of the city mainly in the periphery, with average LST of 35 °C and which commonly transited to asphalt roads (34 °C) and concrete ceilings (32 °C), which together occupied 49% of the city's surface.

Throughout the time scale analyzed (2001, 2011, 2017), the thermal trend is to increase the urban area with extreme discomfort (31 to 33 °C) and stress condition (33 to 35 °C) temperatures, while the areas of pleasant temperatures (<29 °C) decreased between 2001 and 2017 by more than half and are mainly areas with tree cover.

The trend of urban expansion shows a strong competition for space to which the trees are affected, who also; unless they had a minimum covered area of 3 ha, their cooling effect was not perceived in the temperature of the city. It was evident, as shown in the second part of this work, that tree cooled the temperature *in situ*, as happened with individuals at street level; however, their effect was even greater when they were grouped in adequate density, as shown in the comparison between Caña Hueca park and other parks with inadequate maintenance. If the aim is to reduce the temperature of the entire city, it is recommended to intervene in those urban parks with exposed soil and increase the density of trees, in addition to efficiently regulating the change in land use.

The effect of individual trees was studied in the second stage of this work. Although the cooling effect was local, the LST of the tree-shaded sidewalk decreases to 26.5 °C, compared to the adjacent unshaded area. The cooling effect recorded *in situ* is greater than that perceived in the first stage of this research with remote sensing techniques, where the thermal difference ranged from 5 to 10 °C, but its spatial scale of influence was much greater. The individual tree had a great impact on the area below its crown, but this quickly dissipated when the density of the trees was low, on the other hand, when the density increased, the temperature decreases both due to the effect of the shade of the tree as by evapotranspiration, influencing a greater area.

The cooling effect that the shade of tree had inside houses was between 0.96 °C to 1.25 °C and generated environments with thermal oscillations of only 2 °C during the hottest hours of the day. Thermal variation inside a house can be associated with comfort indicators. The last chapter sought to associate the service of the tree as a thermal regulator with an economic estimator. In this case, it was assumed that the shade of the tree on a house was capable of lowering its interior temperature and thus reducing the costs generated by electricity consumption for cooling the house.

The shade of the tree on the house reduced electricity consumption by 32% and also generated a 43% reduction in the associated annual cost. A saving of this magnitude in an average home of 4 inhabitants can mean between $300 and $900 MXN (Mexican pesos) per year depending on the number of appliances and usage habits, and up to $8,300 MXN if the use of air conditioning (AC) is avoided. Thus, using alternative appliances to AC such as fans or waterproofing and painting with a high albedo and combining it with a dense shade of trees can mean significant savings in electricity consumption. In a later exercise, it would be interesting to monitor the single-family cost generated by the annual maintenance of a tree in order to complete the economic balance associated with the shade of the tree.

Finally, some disadvantages or limitations that urban trees have to be implemented as a temperature mitigation strategy are identified: 1) competition for space, 2) appropriate tree selection and 3) a bias perception regarding trees. Various studies have addressed the three limitations in the city of TGZ (Román-Guillén et al., 2019); however, greater awareness is required among the authorities and the population in order to establish concrete actions that are applied throughout the city and in future urban developments.

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APPENDIX

survey: ________________

Date: / / 21

Interviewer: ____

SURVEY TO DETERMINE ELECTRICAL CONSUMPTION FOR DWELLINGS IN COLONIA MONTEREAL, TUXTLA GUTIÉRREZ.

PRESENTATION

Good morning, I am student of the Postgraduate College (COLPOS) who is in the process of graduating and I am carrying out a study to find out the electricity consumption of your home, and how much is spend on cooling.

As you know, in the city of Tuxtla Gutiérrez the use of air conditioning or fans is essential due to the excessive heat, although these devices consume a lot of electrical energy, it is unknown to what extent.

To plan, information from users is needed, because they are the ones who suffer the consequences of the high cost of electricity bills, which is why we are conducting this study. As I cannot visit all the houses, I choose some and yours was selected for the interview, so I am visiting it to ask you some questions. Your personal data are confidential and its use will be exclusive to the study.

GENERAL DATA

Name of respondent: ____ Sex: F _______ M______

Address: ____

Facade color: ____________

Coordinates: X:______________________ Y:_______________________________

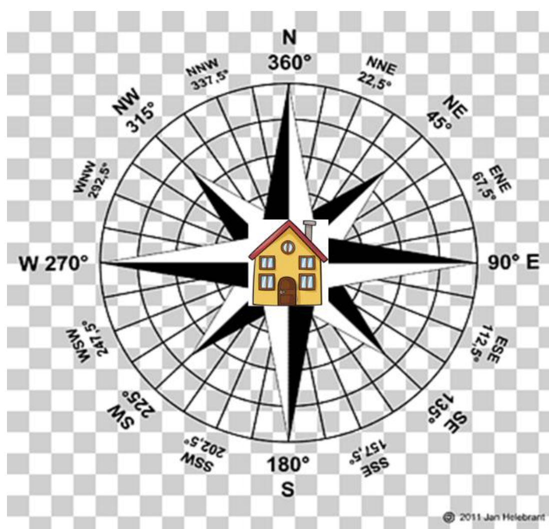
INTERVIEWER (A) Now start the data collection section, which you will answer before starting with the respondent.

I. In this section information will be collected from the <u>TREE.</u> Remember to photograph each tree and name it according to the example: Address + tree number (sepia 365-1).

1. How many meters from the main façade is a tree(s) located? *(Write down the number, one digit per box. If there is no nearby tree, continue to the next section)*

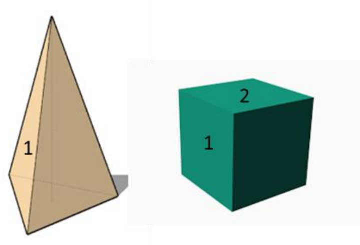
Tree	meters				
1			.		
two			.		
3			.		
4			.		
5			.		

2. In what direction is the tree(s) facing the house? Mark the answer on the drawing.



3. How many faces of the tree are exposed to light? (*Cross out the box corresponding to the number of heads).*

Tree	number of faces



	1	two	3	4	5
1					
two					
3					
4					
5					

4. What is the species of the tree(s)? *(Circle the number of the corresponding option or write down the corresponding answer).*

Species	tree number				
	1	two	3	4	5
Benjamina *(Ficus benjamina L.)*	1	1	1	1	1
Almond *(Terminalia catappa L.)*	two	two	two	two	two
candox *(Tecoma Stans L.)*	3	3	3	3	3
Lemon *(Citrus aurantifolia (Christ) Swingle)*	4	4	4	4	4
Panthon Pine *(Cupressus sempervirens)*	5	5	5	5	5
Palm tree *(Roystonea regia Kunth)*	6	6	6	6	6
Palm tree *(Dypsis lutenscens)*	7	7	7	7	7

Species	tree number				
	1	two	3	4	5
Other:					

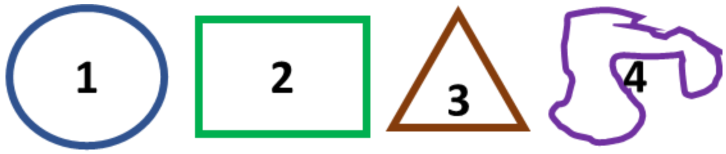
5. What are the location coordinates of the tree? *(Write down the coordinates, one digit per box)*

	East (X)						North (Y)					
1			.				-			.		
two			.				-			.		
3			.				-			.		
4			.				-			.		
5			.				-			.		

6. What is the form factor of the tree? *(Circle the corresponding number).*

			
1	1	0.5	0.25
2	1	0.5	0.25
3	1	0.5	0.25
4	1	0.5	0.25
5	1	0.5	0.25

7. What is the shape of the treetop? *(Write in the box the number that corresponds according to the figure to which the shape of the cup most resembles)*



Tree	
1	
two	
3	
4	
5	

INTERVIEWER (A) Now begins the section of questions that will be answered according to the information provided by the respondent.

II. In this section we will talk about <u>THE INTERVIEWEE'S PERCEPTION REGARDING TREES</u> .

8. Can you mention any benefits conferred by trees? (*Circle the number of the option that corresponds).*

The shade of the tree lowers the temperature	1
They improve air quality	two
Reduces runoff of rainwater	3
Reduces noise caused by cars	4
Reduces the amount of dust in the air	5
Enhance the city landscape	6
Other:	

9. Can you mention any damage caused by trees? (*Circle the number of the option that corresponds).*

Garbage (the leaves)	1
Bench lift (roots)	two
Damage to pipes (roots)	3
Damage to cars (branches)	4
None	5
Other:	

10. What use do you give to fallen tree leaves? (*Circle the number of the option that corresponds).*

	CODE
Pass	1
Does not know	7777
Does not apply	8888
None	9999
Other:	

11. Have you participated in any reforestation campaign? (*Circle the number of the option that corresponds).*

	CODE
Yes	1
Nope	two
Does not know	7777

III. This section will talk about <u>CHARACTERISTICS OF THE HOUSING</u>.

12. Identify the type of dwelling *(You do not require the interviewee to answer this question. Circle the corresponding number).*

Single house on the land ________________ 1	Room on the roof of a building ________________ 4
House that shares land with another (s) __________ 2	Housing in a neighborhood or tenement __________ 5
Duplex, triple or quadruple house ______________ 3	Premises not built for habitation ______________ 6
Apartment in building ____________________ 4	Business premises with room above ____________ 7

13. How many levels does the house have? *(write down the number)*

14. How many adults live in the house? *(write down the number)*

15. How many children live in the house? *(write down the number)*

16. What is the May occupation schedule of the house? *(write down the number)*

Time in 24 hours.

Of: ☐ a ☐

17. What is the orientation of the main façade? *(You do not require the interviewee to answer this question. Circle the corresponding number).*

NE	1	South	two	East	3	West	4

18. What material is most of the walls of the house made of? (*Circle the number of the option that corresponds).*

solid septum	1		Brick	3
hollow septum	two		Other:	0

19. What material is most of the floor in your home made of? (*Circle the number of the option that corresponds).*

cement or firm	two
Mosaic	3
Other:	

20. What material is most of the roof of your home made of? (*Circle the number of the option that corresponds).*

Metal Print	1		Concrete	3
Roof tile	two		Other:	

21. The main insulation of the ceiling. What type is it? (*Circle the number of the option that corresponds).*

red waterproofing	1		tile	5
white waterproofing	two		None	6
Roof tile	3		Does not know	9
Leaf	4		Other	

22. Approximately, how many square meters of construction does your house have? (*Circle the number of the option that corresponds).*

^{Up} to 30m2	1	from 101 to 150 ^{m2}	5
from 31 to 55 ^{m2}	two	from 151 to 200 ^{m2}	6
from 56 to 75 ^{m2}	3	of 201 or more m ^{2}	7
from 76 to 100 ^{m2}	4	Does not know	7777

23. How many exclusive sleeping rooms are there in your home? *(write down the number)*

24. Does your home have...? (*Circle the number of the option that corresponds).*

Living room	1	Main room	6
Kitchen	two	Corridor or hallway	7
Dinning room	3	Guest room	8
Study	4	Laundry room	9
Room	5	Yard	10
Other:			

25. Have you lived here for the last 12 months? (*Circle the number of the option that corresponds).*

Yes	1

Nope	two
Does not know	7777

IV. This section will discuss the <u>ELECTRICITY SUPPLY</u>.

26. In your home, do you have electricity from the public network? (*Circle the number of the option that corresponds).*

Yes	1
Nope	two
Does not know	7777
Other:	

27. May I write down the electricity meter number(s) of the dwelling? (*Circle the number of the corresponding option, and in case of accessing the meter number, write down a figure per box. You can take a photograph of any receipt that you provide and remember to do it on both sides. (If the interviewee does not allow you to record question 20, 21 and 22 follows section V).*

Electricity meter

1												

28. What kind of rate do you have on your meter? (*You do not require the interviewee to answer this question. Circle the number of the option that corresponds).*

	Measurer			Measurer

RATE	1	two
1	1	1
1-A	two	two
1 B	3	3
1 C	4	4

RATE	1	two
1-D	5	5
1-E	6	6
1-F	7	7
DACs	8	8
Does not know	7777	7777

29. How much did I pay in the last two months shown on the last electric bill? *(Write down the number, one digit per box)*

				Receipt date: Months	Receipt date: Year	Meter Termination
$		,				
$		,				
$		,				
$		,				
$		,				
$		,				

V. This section will discuss the <u>TYPE AND USE OF SPOTLIGHTS.</u>

30. Approximately how many light bulbs does your home have? (*Circle the number of the option that corresponds).*

number of foci			
5	10	fifteen	over 15

31. What kind of bulbs do you usually buy? (*Circle the number of the option that corresponds).*

1. fluorescent savers	1
2. LED savers	two
3. Incandescent	3
Does not apply	8888
Does not know	9999

32. How many watts are the bulbs you usually buy? (*Enter one digit per box).*

1. fluorescent savers		
2. LED savers		
3. Incandescent		

Does not apply	8888
Does not know	9999

VI. This section will talk about <u>APPLIANCES.</u>

33. How many of these appliances do they have? (*Write the number as appropriate. If you do not have the appliance, write down the number zero).*

1. microwave		10. refrigerator	

2. blender		11. Screen (TV)		*In case of zero omit 35 and 36*
3. blender		12. Ceiling fan		*In case of zero omit 40 and 41*
4. coffee pot		13. Standing fan		
5. toaster		14. tower fan		
6. electric oven		15. Game console		
7. hair dryer		16. washing machine		
8. hair straightener		17. electric ignition stove		
9. clothes dryer		18. air conditioning		*In case of zero omit 42 to 45*

34. Tell me if the equipment that I am going to mention in the home has or had a yellow label for energy efficiency and a FIDE seal, like the ones I am going to mention. (*Listen and write down the code as appropriate).*

	YELLOW LABEL	
1. Refrigerator?		
2. Washing machine?		
3. Air conditioning?		
4. Stove?		

Yes	1
Nope	two
Does not know	9999

35. Is the television or screen you have of the type...? (*Write down the code for each television if there is more than one).*

CODE	TV

OLED	1		1			
leds	2		2			
LCD or plasma	3		3			
analog	4		4			
Does not know	7777		5			

36. How many inches is the television? (*Write down the code as appropriate for each television).*

CODE	
Less than 30 " (very small)	1
Between 30 and 39 " (girl)	2
Between 40 and 49 " (medium)	3
Between 50 and 60 " (large)	4
Greater than 60 " (extra large)	5
Does not know	7777

TV				
	1			
	2			
	3			
	4			
	5			

VII. In this section we will talk about <u>AIR CONDITIONING.</u>

37. In your opinion, what are the months in which you feel the most heat inside your home? *(Circle the corresponding code).*

MONTHS

JAN	FEB	SEA	APR
1	two	3	4
MAY	JUN	JUL	AUG
5	6	7	8
SEP	OCT	NOV	DEC
9	10	eleven	12

38. In your opinion. What is the hottest room in your house?

Living room	________	1	Main room	________	6
Kitchen	________	two	Corridor or hallway	________	7
Dinning room	________	3	Guest room	________	8
Study	________	4	Laundry room	________	9
Room	________	5	Yard	________	10
Other:			None		

39. Do any rooms in your house receive tree shade?

Living room	________	1	Main room	________	6
Kitchen	________	two	Corridor or hallway	________	7

Dinning room	3	Guest room	8
Study	4	Laundry room	9
Room	5	Yard	10
Other:		None	9999

40. Which rooms have a ceiling fan? *(If the interviewee does not have a ceiling fan, skip questions 33 to 34. Circle the corresponding code).*

Living room	1	Main room	6
Kitchen	two	Corridor or hallway	7
Dinning room	3	Guest room	8
Study	4	Laundry room	9
Room	5	Yard	10
Other:		None	9999

41. Approximately how many hours a day is the ceiling fan on? *(Write down the number. One digit per box)*

HOURS

42. Which rooms have air conditioning? *(If the interviewee does not have air conditioning, skip questions 35 to 40. Circle the corresponding code).*

Living room	1	Corridor or hallway	7
Kitchen	two	Guest room	8
Dinning room	3	Laundry room	9
Study	4	Yard	10
Room	5	Study	eleven
Main room	6	None	9999

43. Approximately how many hours a day is the air conditioner on? *(Write down the number. One digit per box.)*

HOURS

44. At what temperature do you turn on the air conditioning? (*Circle the number of the option that corresponds).*

less than 18°C	1
between 18 and 20°C	two
between 21 and 25°C	3
over 25°C	4
Does not know	7777

Does not apply	8888

45. What type of air conditioning do you have? (Write down *the number as appropriate. If possible take a photograph of the technical sheet of each team).*

Laptop	
window	
mini-split	

mini-split inverter	
Other:	

Does not apply	9999
Does not know	7777

46. What brand is your air conditioner? (*Circle the number of the option that corresponds).*

Mirage		1
LG		two
Samsung		3
Hisense		4
Does not know		777
Other:		

47. What is the maximum consumption (kwh) of your air conditioner? (*Write down the consumption. This information can be located on the labels of each equipment).*

	1	2	3	4
Laptop				
window				
mini-split				
mini-split inverter				
Another type				
Does not know				
Does not apply	9999			

48. What is the voltage of your air conditioner? *Write down the code for each air conditioner.*

1	
2	
3	
4	

220 volts	1
110 volts	two
Does not know	7777
Does not apply	9999