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Vegetation as a Regulator of Urban Climate: the Case of the Guadalajara Metropolitan Zone, Jalisco, Mexico

La vegetación como reguladora del clima urbano: el caso del Área Metropolitana de Guadalajara, Jalisco, México

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Abstract: The growth of urban areas has led to deforestation and consequently the loss of climatic regulation service, which typically results in temperature increases. Urban warming, a product of this deforestation, can pose hazards to public health and quality of life. Like other cities in Mexico and globally, the Guadalajara Metropolitan Area (GMA) has been characterized by rapid demographic and urban growth with vegetation losses that induce the formation of Urban Heat Islands (UHIs). Using the Enhanced Vegetation Index (EVI), vegetation density and its changes over recent decades in the GMA are evaluated. It is observed that vegetation has decreased between 1980 and 2020. This land use change has generated a UHI and consequently the loss of climatic comfort for the population, with an increase of 2 to 3ºC in the GMA. The UHI raises the probabilities of reaching conditions of comfort deemed perilous. By employing the Heat Index (HI), computed from surface temperature and atmospheric humidity data, it is found that the probabilities of it exceeding 30ºC have risen by around 10% in 30 years, primarily in the eastern part of the GMA, equivalent to almost an extra month of conditions outside the range of comfort considered appropriate. In the Municipality of Guadalajara, there is a deficiency in green areas, therefore, this urban area cannot be deemed a healthy city according to UN criteria. Consequently, the environmental policy of urban GMA must lead to the recovery and protection of vegetation and ecosystem services.

Keywords: deforestation, urban areas, quality of life, heat islands.

Resumen. El crecimiento de las áreas urbanas ha provocado deforestación y con ello la pérdida del servicio de regulación climática, que generalmente resultan en aumentos de la temperatura. El calentamiento urbano, producto de dicha deforestación, puede resultar en peligros para la salud y la calidad de vida de la población. Al igual que otras ciudades de México y el mundo, el Área Metropolitana de Guadalajara (AMG) se ha caracterizado por un rápido crecimiento demo-

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gráfico y urbano con pérdidas de vegetación que inducen la formación de Islas de Calor Urbana (ICU). Mediante el uso del Índice Mejorado de Vegetación (EVI, por sus siglas en inglés), se evalúa la densidad de vegetación y sus cambios en décadas recientes en el AMG. Se encuentra que, entre 1980 y 2020, la vegetación decrece. Dicho cambio en el uso de suelo ha generado una ICU y con ello la pérdida de confort climático para la gente, con un aumento de entre 2 y 3ºC en el AMG. La ICU aumenta las probabilidades de llegar a condiciones de confort consideradas peligrosas. Utilizando el Índice de Calor (IC), calculado a partir de datos de temperatura y humedad atmosférica de superficie, se encuentra que las probabilidades de que éste rebase los 30ºC ha aumentado en alrededor de 10% en 30 años, principalmente al oriente del AMG, lo que equivale a casi un mes adicional con condiciones fuera del rango de confort consideradas adecuadas. En el Municipio de Guadalajara, se tiene carencia de áreas verdes por lo que esta urbe no puede ser considerada una ciudad saludable, de acuerdo con los criterios de la ONU. Por ello, la política ambiental del AMG urbana debe llevar a la recuperación y protección de la vegetación y los servicios ecosistémicos.

Palabra clave: deforestación, áreas urbanas, calidad de vida, islas de calor.

INTRODUCTION

Urban areas occupy less than 1 % of the Earth's surface and are home to more than half of the global population (UNDP, 2020). In 1950, 70 % of the world's inhabitants lived in rural settlements, but in 2007, the urban population exceeded the rural population (UN, 2020). The United Nations (UN, 2020) estimates that by 2050, the percentage of people in urban areas will increase to 68 % and, therefore, sustainable development and a good quality of life in cities will be less likely. This situation will depend on urban planning, especially in low- and middle-income countries. In Mexico, 79 % of the total population lived in urban areas in 2020, and it is estimated that it will reach 83 % by 2030 (INEGI, 2020), so planning urban growth is of great importance.

The growing demand for housing and infrastructure is often met by urban expansion, which involves the clearance of natural vegetation and a reduction in ecosystem services (e.g., Mohammadyari *et al.*, 2023). In Mexico, the growth model of cities has followed these dynamics, which has led to the loss of regulation services, including lower carbon storage (e.g., Guillen-Cruz *et al.*, 2021), a decrease in the regulation of extreme weather events (e.g., López *et al.,* 2020), and a trend towards dangerous levels of climate change (e.g., Behzadi *et al.*, 2020). The loss of natural landscape, particularly vegetated areas, has modified the urban climate (Oke *et al.*, 2017), inducing an increase in the frequency and intensity of meteorological events such as heat waves (IPCC, 2001; Jáuregui, 2009; Lu *et al.*, 2023). The work of Jáuregui (e.g., 2004) has documented that Mexican cities with more than one million inhabitants produce Urban Heat Islands (UHIs), which grow in area and intensify over time until they become a danger to the local inhabitants.

The so-called *urban green infrastructure* is a planned network of high-quality natural and semi-natural areas designed and managed to provide a wide range of ecosystem services that help protect biodiversity in urban environments (European Commission, 2013). This green infrastructure deteriorates with the formation of a UHI. The Guadalajara Metropolitan Zone (GMZ) has lost greenness and, with it, climate-regulating ecosystem services (Camacho-Sandoval, 2022).

Since the late twentieth century, Ernesto Jáuregui (1987, 1997) documented the formation of a UHI on GMZ due to increasing urbanization. GMZ UHI has led to more frequent intense heat events and changes in the local hydrological cycle (López *et al.*, 2022), with a tendency to a higher frequency of heavy rains in a vulnerable city, which has increased the risk and incidence of urban flooding.

Despite changes in the local climate, GMZ is also an area of opportunity to implement nature-based climate risk management measures and strategies (Jiménez, 2022), where the recovery of green infrastructure plays a central role. Some studies on UHI mitigation show that ecosystem services mitigate changes in urban climate that bring about several health benefits (Colunga *et al.*, 2015; Chen *et al.*, 2019). Both mitigation and adaptation to climate change can be achieved from the recovery and consolidation of green infrastructure, thus improving urban sustainability and the health of socio-ecosystems (Salmond *et al*., 2016). However, strategies are required to show that the recovery of ecosystem services in urban areas can reach levels that generate healthy cities (Pineo *et al*., 2018). Recovery of green infrastructure will alleviate climate risk by reducing hazards and vulnerability.

Green infrastructure in urban environments not only beautifies cities but mainly plays a central role in mitigating climate change (Venn and Niemela, 2004). Trees confer color and scenic beauty to cities and reduce the dangers of UHIs (Cruz-Sandoval *et al*., 2020; Ziter *et al*., 2019; Duncan *et al*., 2019) that result from an increased abundance of asphalt, concrete, steel, and glass (Schwaab *et al*., 2021). Urban areas covered with trees and grass reduce temperatures by two to four times compared to urban areas without vegetation (Cruz-Sandoval *et al*., 2020; Schwaab *et al*., 2021).

Areas such as GMZ face problems derived from the loss of vegetation and intensification of UHIs (Jáuregui *et al*., 1992; Alamilla Chan & Davydova Belitskaya, 2020). In late spring and early summer, temperatures exceed 38 °C in the eastern GMZ zone, with heat waves; in June 2005, 11 deaths occurred in the state of Jalisco due to this meteorological condition (Curiel, 2014). In more recent years, such as June 2023, the intense heat reached maximum temperatures of nearly 40 °C.

Strategies to manage the risks of climate change in large cities should consider mitigating UHIs. Doing so implies estimating the extent of mitigation with actions such as urban reforestation. Within the framework of this approach, the objective of this study is to diagnose the characteristics and dynamics of the green infrastructure of GMZ between the years 2000 and 2018 and their relationship with climatic comfort conditions. Assessing the relationships between green infrastructure and thermal comfort will make it possible to propose actions to make GMZ a healthy city.

DATA AND METHODOLOGY

GMZ is the largest city in the state of Jalisco and is located in western Mexico (Figure 1). It comprises the urban areas of nine municipalities and extends over 62,645 hectares that harbor approximately 5,268,642 inhabitants (IIEG, 2020).

To estimate green infrastructure in GMZ, the density of green areas per inhabitant was calculated based on the latest IIEG census (2020) and the following urban planning instruments: Municipal Urban Development Programs (PMDU), Partial Urban Development Plans (PPDU), and Urban Development Plans of the Population Center (PDUCP), in addition to information obtained

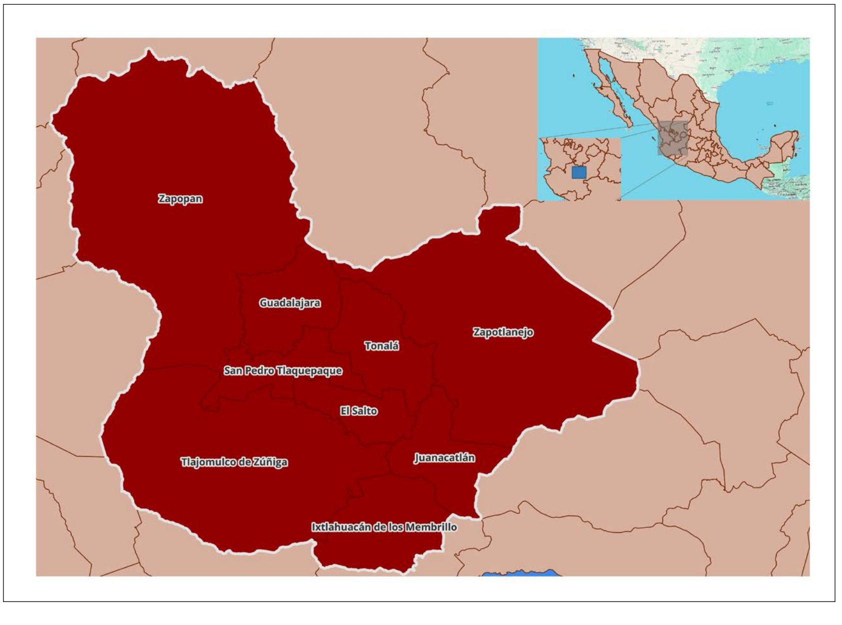


Figure 1. Municipalities of the Guadalajara Metropolitan Zone in western Mexico. Sources: Own elaboration with data from INEGI (2020) and IIEG (2020).

from Open Street Map, including information on roundabouts and medians from INEGI's 1:20,000 topographic charts and from protected natural areas (federal, state, and municipal); IIEG, 2018).

The evolution of green infrastructure in GMZ in general and the municipality of Guadalajara in particular was also documented through information from the Enhanced Vegetation Index (EVI) provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) satellite (GSFC, 2022) and Landsat. This index has a spatial resolution of 250 meters × 250 meters, with compounds spanning 16 days for the period 2000 to 2019 (https://www.climateengine.org).

The climatic conditions of GMZ were characterized using daily maximum and minimum temperature and precipitation data recorded at stations of the National Water Commission (CONAGUA) inside and outside GMZ for the period 1960–2018 (available at https://smn.conagua.gob.mx/es/climatologia). Hourly data from the Jalisco Secretariat of Environment and Territorial Development (SEMADET) monitoring network were also used from ten stations located in GMZ where humidity and wind are monitored in addition to temperature.

Daily and hourly weather data from GMZ were interpolated into a regular 4 km × 4 km grid using a scheme by Cressman (1959). The weather field grids correspond to data provided by Magaña (personal communication, 2023). With the temperature and humidity fields, the Heat Index (HI) for GMZ for 2000–2018 was calculated, following the proposal of the United States Oceanic and Atmospheric Administration (NOAA, 2022) given by the equation:

$$HI = -42.379 + 2.04901523 * T + 10.14333127 * RH - 0.22475541 * T * RH - 0.00683783 * T * T - 0.05481717 * RH * RH + 0.00122874 * T * T * RH + 0.00085282 * T * RH * RH - 0.00000199 * T * T * RH * RH$$

where T is temperature in degrees Fahrenheit (°F) and RH is relative humidity in percentage (%). For clarity purposes, the HI was expressed in degrees Celsius.

Using a scheme of successive corrections (Cressman, 1959), daily HI fields for GMZ were calculated on regular grids.

Land surface temperature (LST) data were also analyzed based on images from the Landsat platform (https://www.climateengine.org) with spatial and temporal characteristics similar to those of EVI. The analysis was supplemented with a short sampling (three days at the time of day when the maximum temperature is reached) at sites near an urban park to estimate the effect of trees and land cover on temperature, humidity, and wind speed. Measurements were recorded in the area adjacent to the Los Colomos Forest, located in the northeast of the Guadalajara municipality. The measurements were carried out for three hours at five sites separated by 500 meters radially away from the park, every ten minutes, between 13 and 15 March 2022, from 3:00 p.m. to 5:00 p.m.

RESULTS

Urbanization and Green Infrastructure in GMZ

The expansion of GMZ in recent decades (2000–2020) has been characterized by a change of land use from areas of natural vegetation or agriculture to areas with urban infrastructure. In GMZ, green areas are divided into three categories: 1) natural protected areas (NPAs), which are regions that have not suffered significant alterations by human activity and are under legal protection, fulfilling crucial ecological functions; 2) green spaces in the urban area of GMZ as part of urban planning, which comprise areas for leisure and use; and 3) urban forests, as defined by the Metropolitan Land Use Plan of GMZ, which are considered of high environmental value and relevance for ecosystem conservation.

The World Health Organization (WHO) and UN-Habitat suggest a minimum of nine square meters of green space per inhabitant and that all residents have access to a green area by walking a maximum of 15 minutes. In GMZ, 40 % of the neighborhoods lack sufficient green infrastructure. Another 40 % of the neighborhoods have more than 30 square meters of green areas per inhabitant, but they are located at the periphery of GMZ in neighborhoods near the Huentitán ravine in the northern part of the Guadalajara municipality. The remaining 20 % of the neighborhoods have a green area between 9 m^2 and 20 m^2. Only 30 neighborhoods have more than 30 % and up to 64 % of their surface with green areas that correspond mainly to parks or areas of preserved natural vegetation (Figure 2a). EVI data for September 2020 made it possible to identify the areas with the greatest greenery that correspond to green infrastructure (see Figure 2b).

In the Guadalajara municipality, 221 neighborhoods (78 %) are below the recommended vegetation parameter, making this the municipality with the greatest deficiency of green areas in GMZ. The 2018 Metropolitan Forest Management Plan (POFMet) estimated that there are 1,158,009 trees in public spaces, mainly along roadsides, and only a small number in parks and gardens in the metropolitan area. This record does not include trees in protected natural areas, managed public parks, private properties, or rural areas. Thus, in the Guadalajara municipality, 47 % of urban trees are located in public spaces such as roundabouts, medians, and sidewalks; 38 % in front courtyards and neighborhood green areas; 4 % and 8 %, respectively, in parks and the ravine; and 2 % in private gardens inside houses. Neighborhoods with a high population density lack green infrastructure and are located mainly in the central GMZ area. The northeast of the Guadalajara municipality is home to the largest population of children and adolescents; however, this area has insufficient urban trees or green spaces for recreation. In contrast, the neighborhoods with the highest amount of green infrastructure and urban trees have a relatively lower population density and a higher socioeconomic level, such as near Los Colomos Forest, in the northwest of Guadalajara.

The mean annual greenery condition estimated from EVI data for 1991–2000 allows for identifying

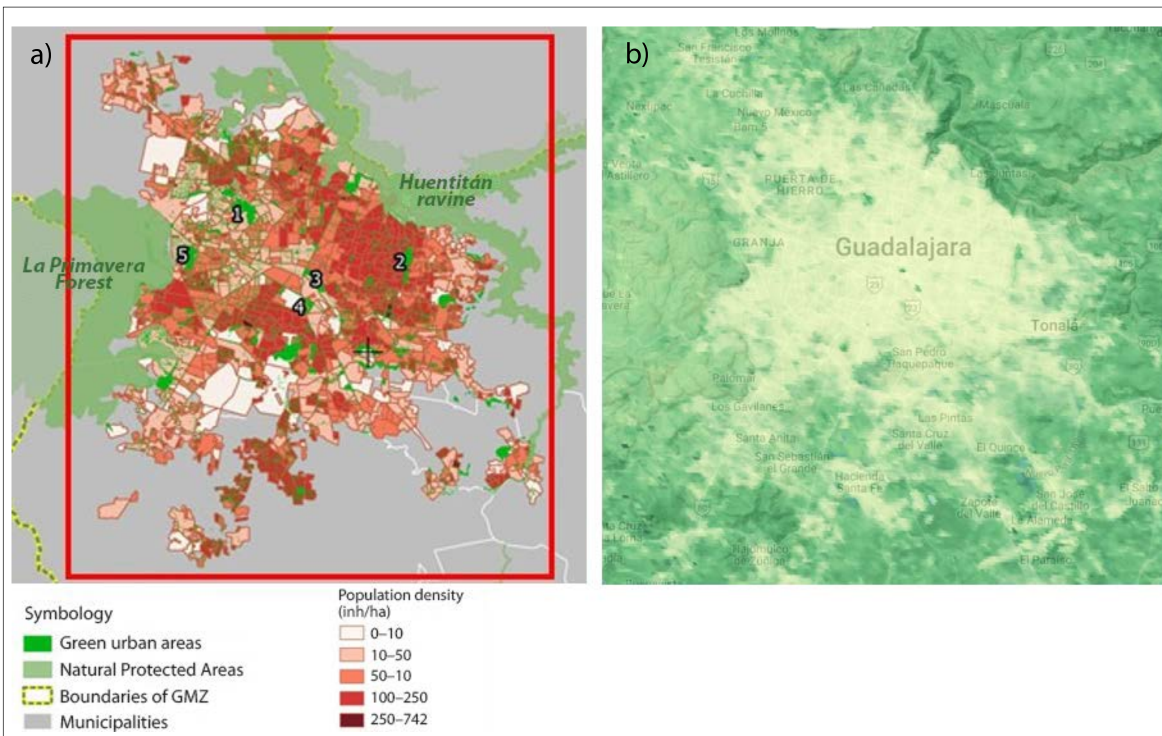


Figure. 2 a) Population density and urban green spaces in GMZ at the neighborhood level, and b) the EVI condition for September 2020. Source: Own elaboration with INE-IIEG 2018, INEGI 2020, and MODIS data from ClimateEngine.org.

the urbanized area of GMZ. EVI values below 0.02 correspond to scarce vegetation, characteristic of urbanization, while the periphery shows EVI values above 0.2, with a greater natural vegetation cover (Figure 3a). Excluding the 49,743 hectares corresponding to the protected natural areas located on the periphery of GMZ, green spaces cover an area of 4697 hectares, that is, 7.5 % of the total area of GMZ. In the past decade (2011–2020), the urban area expanded and the greenery decreased (Figure 3b). GMZ had a population of 5,179,874 inhabitants in 2020 (INEGI 2020), an area of 2551.34 km^2, and a population density of 2145 inhabitants/km^2. Zapopan (9721 inh/km^2), Tonalá (4483.28 inh/km^2), and El Salto (4420 inh/km^2) are the most densely populated municipalities in GMZ and those most exposed to climate hazards.

From 1991, GMZ recorded urban growth toward its periphery, characterized by a significant loss of natural vegetation (Figure 4), for example, toward the Tlajomulco and Tlaquepaque municipalities in the southwest and Tonalá in the east, resulting in the loss of ecosystem services, particularly regulatory services that lead to a reduction in climatic comfort.

Changes in the spatial distribution of EVI values from 2000–2005 to 2017–2022 in two seasons (dry and rainy) revealed changes in the greenness condition of GMZ throughout the twenty-first century. In the dry season (April) of 2000–2005, the EVI index was mainly in the range of 0.1 to 0.2 (Figure 5a), indicating vegetation under high water stress or areas without vegetation. In this period, more than 80 % of EVI values were between 0.1 and 0.2, and only 2 % were between 0 and 0.1. However, in 2017–2022, the percentage of EVI values between 0.1 and 0.2 decreased to 60 %, while values from 0 to 0.1, which correspond to areas without vegetation, increased significantly (more than 20 %). This trend becomes clearer when the wet period is analyzed, i.e., when the vegetation is healthier. At the end of the rainy season (September) of the period 2000-2005, the highest frequency of EVI values (about 45 %) was between 0.4 and 0.5, and just over 20 % were between 0.5 and 0.6. However, in the wet period of 2017–2022, the frequency of EVI values between 0.4 and 0.5 dropped to 37 %, and EVI values from 0.5 to 0.6 corresponded to only 12 % (Figure 5b). This analysis shows that urban green infrastructure has been significantly reduced, and areas without vegetation have increased over a period of around 15 years. In general, vegetation loss has resulted from land use changes to asphalt, concrete, steel, and glass associated with the urbanization process.

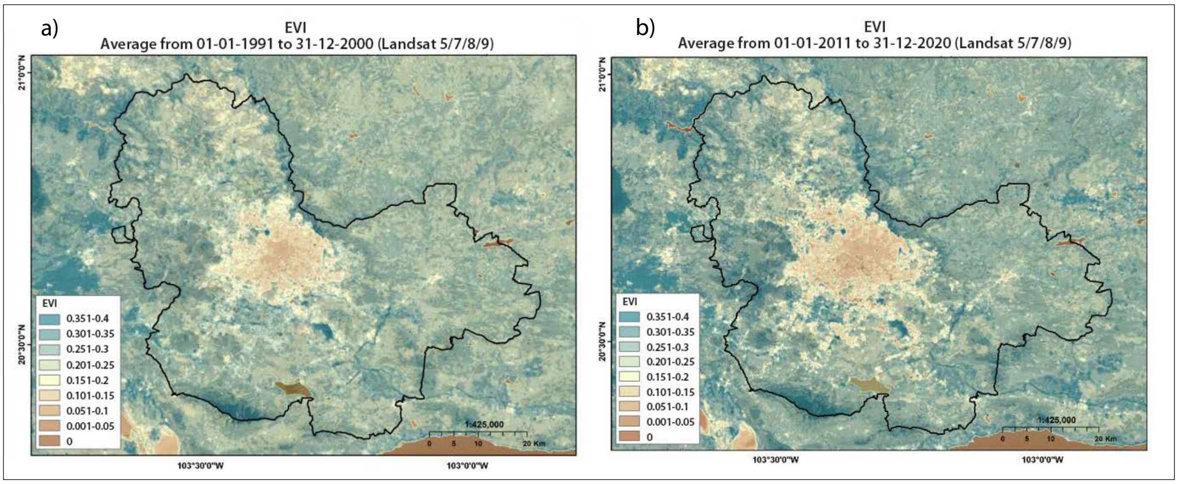


Figure 3. Mean annual EVI for periods a) 1991–2000 and b) 2011–2020. Source: Own elaboration with EVI Landsat data from ClimateEngine.org.

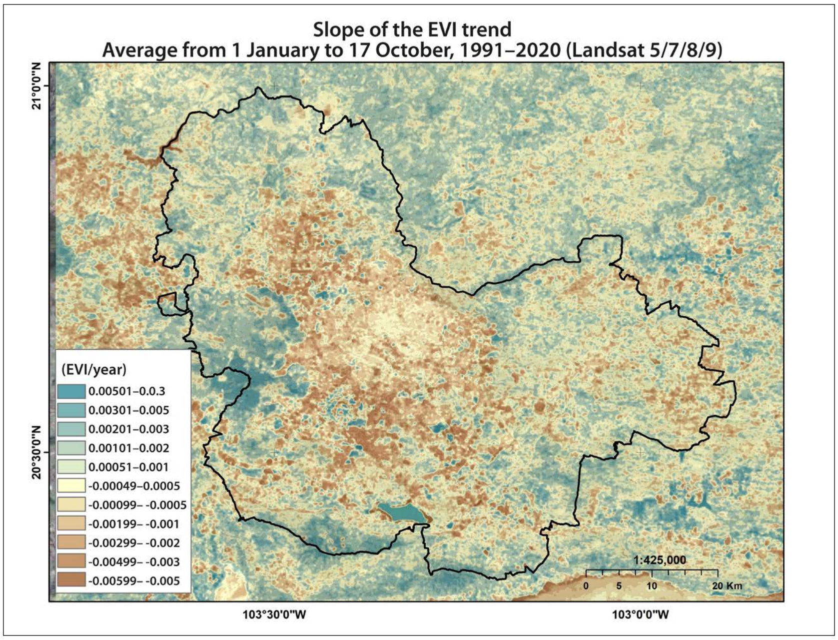


Figure 4. Difference in greenness-EVI level in GMZ between 1991 and 2020. Source: Own elaboration with Landsat data from climateengine.org

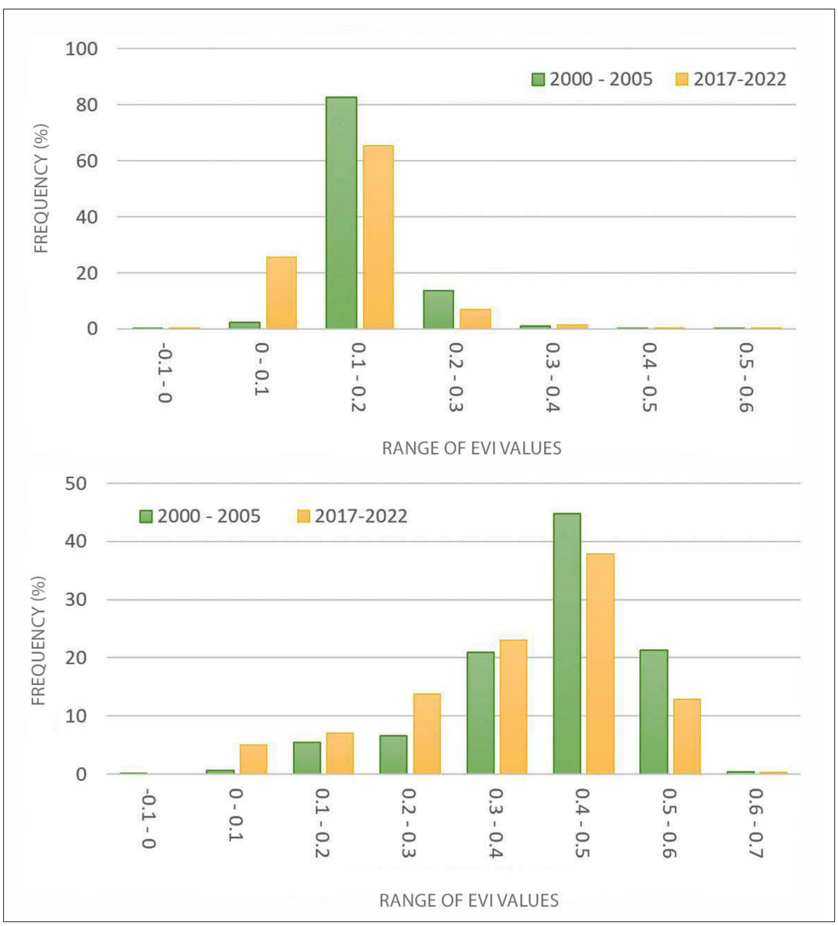


Figure 5. Contrast in the distribution of EVI values (between 0 and 1) between the periods 2000–2005 and 2017–2020, a) for the dry season (April) and b) for the rainy season (September).

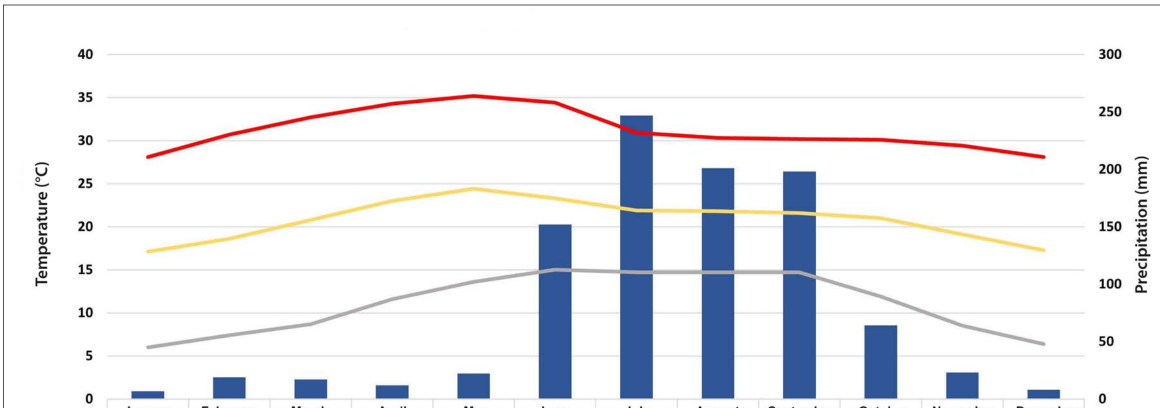
The Comfort Index in a Changing Environment and Climate

The climate of GMZ is monsoon-type, with a rainy season between June and October and a dry season between November and May. Peak maximum and minimum temperatures occur between April and June, before the start of the rainy season. Although the mean maximum temperature in May or June is close to 35 °C (Figure 6), the temperature can exceed 38 °C in days of intense heat.

In the last 60 years, the average temperature in GMZ has increased by around 2 °C, and the number of days with maximum temperatures above 35 °C has doubled. To illustrate this trend, the analyses of maximum temperatures in the Tonalá municipality in three ten-year periods (1991–2000, 2001–2010, and 2011–2020) are shown (Figure 7). For the first period, 1991–2000, temperatures above 36 °C were not recorded, and the highest frequencies were concentrated at 26 °C, followed by 24 °C and, in third place, 28 °C. For 2001–2010, temperatures of 28 °C, 30 °C, and 32 °C recorded the highest frequencies. Furthermore, temperatures of 38 °C appeared, which were not recorded 30 years earlier (Figure 7). In the decade 2011–2020, the main change regards the increase in the frequency of high maximum temperature values.

In recent years, the greenness level estimated through the EVI (Figure 8a) and the land surface temperature (Figure 8b) shows a similar spatial pattern, reflecting the relationship between land use (greenness level) and land surface temperature. In the spring months, the land temperature is higher in areas where the EVI is low, such as in the central area of the Guadalajara municipality or in regions with bare soil. In Barranca de Huentitán and areas with a greater green infrastructure, the EVI index increases, and the land surface temperature is lower.

The Tonalá municipality, located in the east GMZ, shows one of the largest trends in deforestation, loss of greenery, and an increase in the land surface temperature. This region has experienced the greatest reduction in comfort level and concentrates the largest real estate developments in GMZ. The heat index or comfort index combines air surface temperature and relative humidity to assess the thermal sensation of the human body (NOAA, 2022). Atmospheric humidity impacts the body's ability to regulate its temperature under warm conditions, so it is important to calculate the temperature that the body senses under the influence of high temperature and humidity conditions to prevent adverse health effects. When humidity is high, perspiration becomes inefficient; this



	January	February	March	April	May	June	July	August	September	October	November	December
Pp	6.7	18.9	17	11.9	22.3	152.1	247	201.1	198.1	64.3	23.2	8.2
Tmax	28.1	30.7	32.7	34.3	35.2	34.4	30.9	30.3	30.2	30.1	29.4	28.1
Tmin	17.1	18.6	20.8	23	24.4	23.3	21.9	21.8	21.6	21	19.1	17.3
Tmed	6	7.4	8.7	11.6	13.6	15	14.7	14.7	14.7	11.9	8.5	6.4

Figure 6. Precipitation and mean temperature in the city of Guadalajara (1991–2020). Source: Institute of Astronomy and Meteorology of the University of Guadalajara (2020).

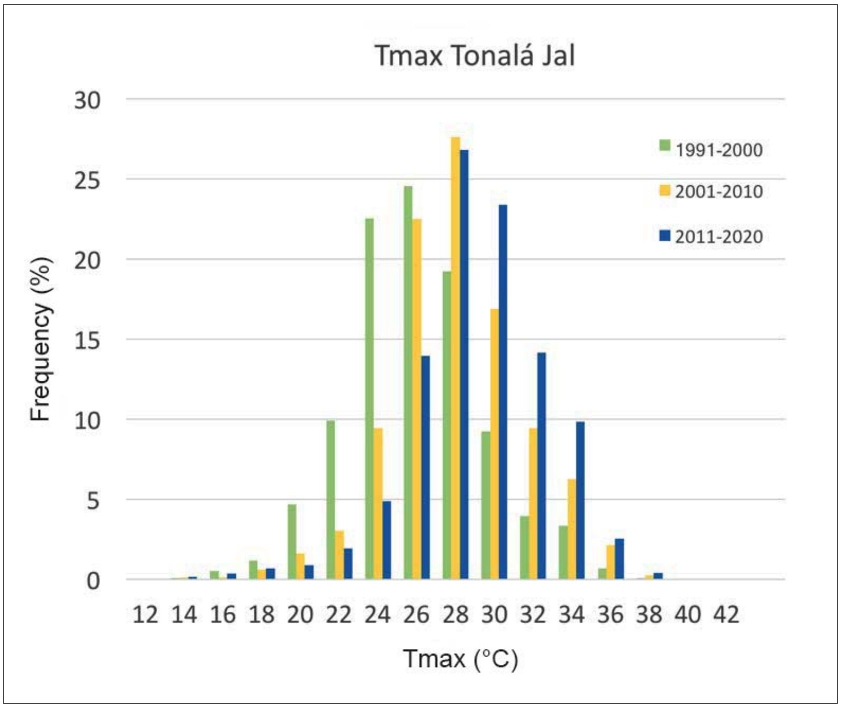


Figure 7. Maximum temperatures in the Tonalá municipality.

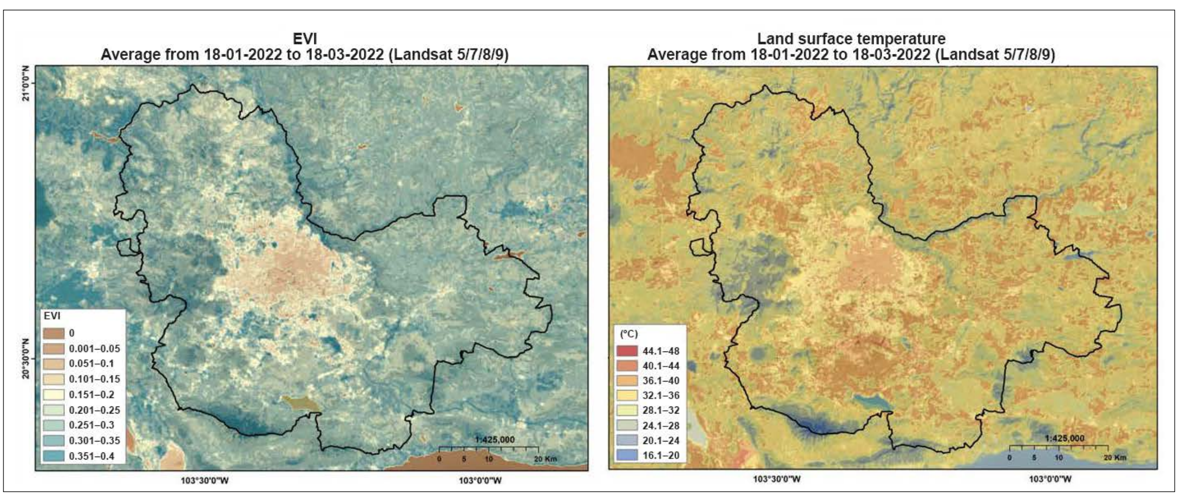


Figure 8 a) Average EVI and b) land surface temperature above GMZ for the period 2020–2023. Source: Own elaboration with data from the Climate Engine platform.

increases the thermal sensation because the body does not manage to cool itself properly.

For the present study, the heat index, also known as the thermal comfort index, was calculated from daily maximum temperature and relative humidity data in a range in which it differs from the maximum temperature due to the effect of atmospheric humidity, i.e., for temperatures above 27 °C and relative humidity above 40 %. The daily heat index between two time periods, 1981–2000 and 2000–2018, was calculated using data from the Secretariat of Environment and Territorial Development (SEMADET) weather stations and the CONAGUA network. Considering that the clearest climate change signal is detected at extreme values (IPCC, 2007), the probability of a HI above 30 °C in GMZ and its urban area was analyzed. Contrasting the HI between the two periods allowed us to establish how the UHI generates a climate hazard. Between 1981 and 2000, the highest odds of HF > 30 °C were recorded in the eastern part of GMZ, with values above 30 % (Figure 9a). Urban growth and deforestation, which were marked to the east and south of GMZ, increased the probability of HI > 30 °C by at least 10 % for the period 2000–2018 (Figure 9b), thus reaching a probability that the CI > 30 °C up to 40 %. This means that, in previous decades, with a smaller urbanized area, you could have more than 120 days with a HI above 30 °C. Today, the duration can be around 140 days, representing a longer season of intense heat that is dangerous in a densely populated area. If the same risk analysis is performed for probabilities of HI > 33 °C, the odds are less than 20 %, and the increase is less than 5 % with each decade. The odds of an HI above 35 °C remain almost constant between the two periods.

In areas where greenery conditions are reasonably preserved, changes in the probability of increased HI are relatively small. This shows that, for HI ranges deemed hazardous, the UHI increases the probability of reaching conditions that NOAA considers dangerous, in which extreme care or care must be taken, mainly regarding the most vulnerable population sector.

Land Use and Environmental Temperature

To show the climate regulation services provided by trees, measurements of surface atmospheric temperatures were recorded at five sites near Los Colomos Forest. The effects of differences in land use were explored by recording the temperature and relative humidity every ten minutes between 3:00 p.m. and 5:00 p.m. (the time when maximum temperatures are reached) over three days (13 to 15 March 2022) (Figure 10).

The temperatures for the three days of measurement are generally lower in the wooded area near the forest (site 1) than in the surrounding areas. In contrast, in areas without vegetation (site 3), solar radiation heats the ground (asphalt), and the air temperature is higher, as is the case on the street. At sites 2 and 4, the measured temperature depends on the dominant land use; it is generally lower than in the asphalt area without vegetation but higher than in the wooded area. Data from the automated weather station (EMA, in Spanish) within Los Co-

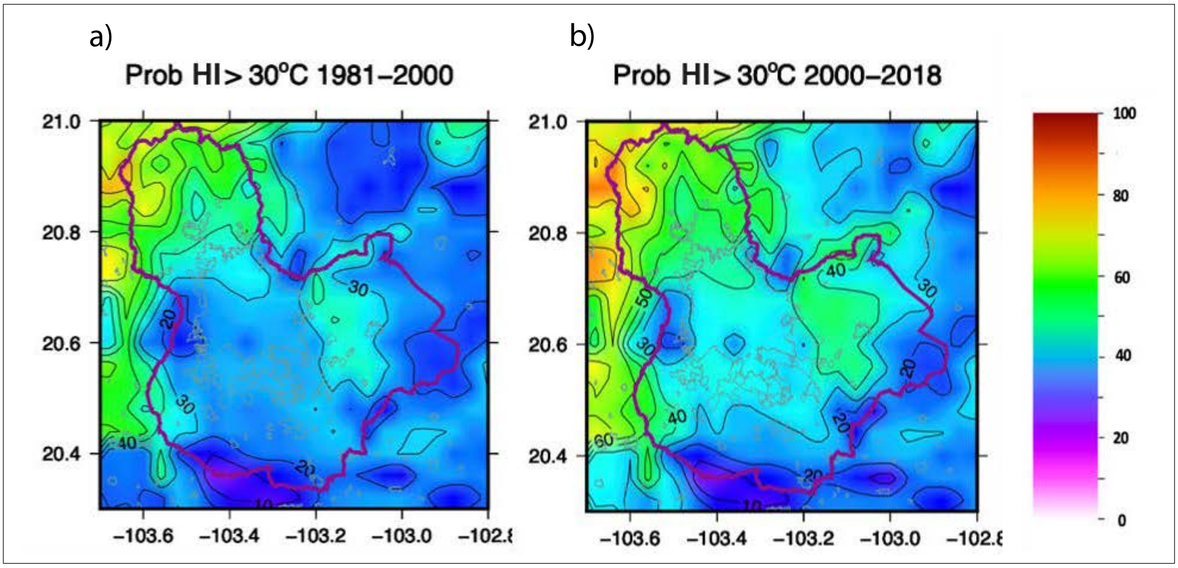


Figure 9. Probability of HI > 30 °C for two periods: a) 1981–2000 and b) 2000–2018. Source: Own elaboration with data provided by the Institute of Geography-UNAM.

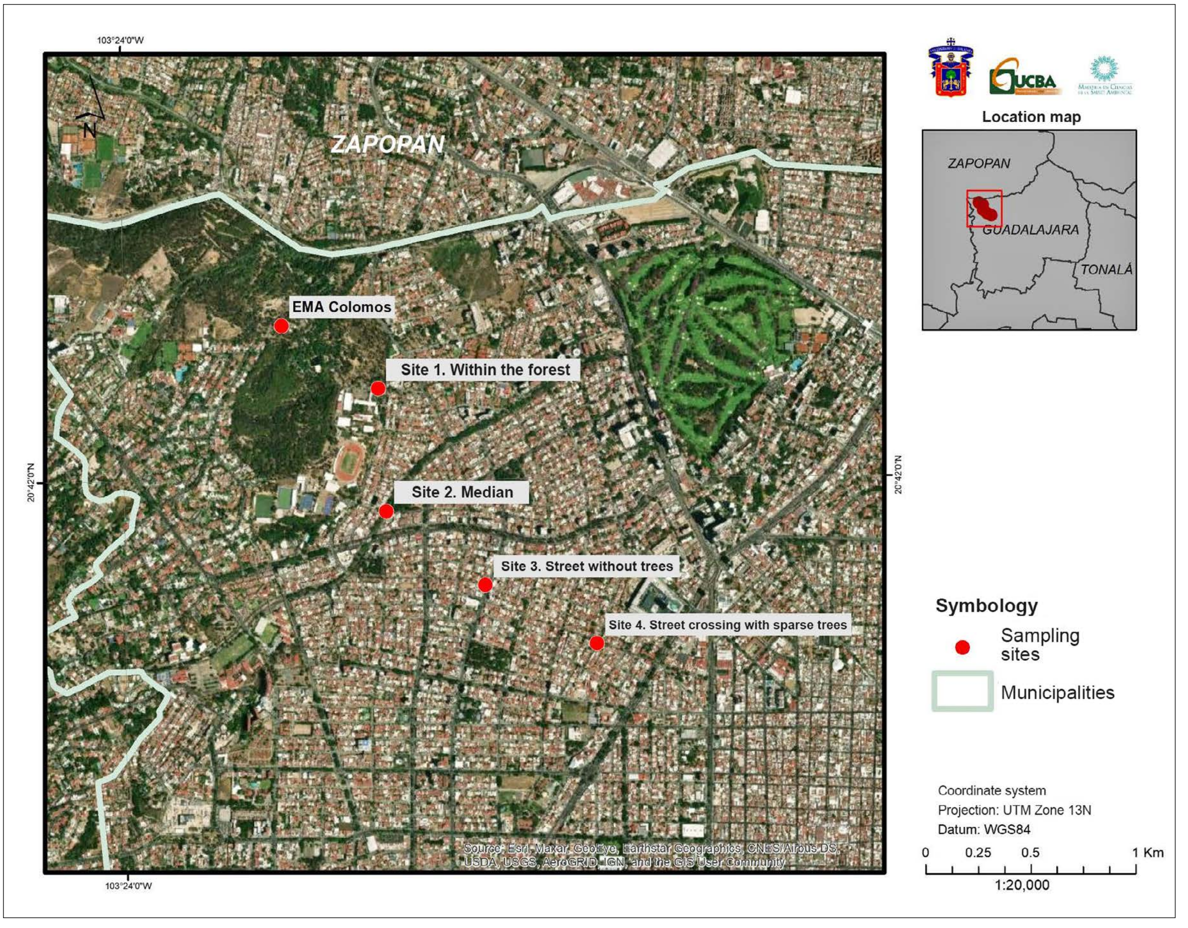


Figure 10. Location of sampling points. Source: Own elaboration with data from Google Earth.

lomos Forest were used as a reference even though there are no trees around it. The temperature within the park is comparable to that of sites with a certain proportion of vegetation (sites 2, 4, and 5). Green infrastructure helps regulate maximum temperatures even without being directly in the shade, so urban areas with trees are generally cooler than those with sparse vegetation (Figure 11). On average, records of near-surface air temperature indicate a difference of up to 4 °C between a site with trees and an area without vegetation.

Relative humidity in the wooded area is generally higher than in the asphalt-covered area. Although a higher humidity tends to produce a slight increase in the thermal sensation given by the HI, the lower maximum temperature leads to a HI within the adequate range. The wind speed in the sample was generally very weak (less than 2 m/s) in the study area, so its cooling effect by heat advection ("fresh air") was insignificant. During the measurement campaign, the wind coming from Los Colomos Forest was observed to produce a cooling effect by advection of cooler air towards urbanized areas.

The land surface temperature obtained from Landsat satellite images for the spring months (2022-01-18 and 2022-03-18) indicates that the land temperature is generally lower in sites with more vegetation than in areas where urbanization dominates (Figure 12a). In the LST image, these correspond to areas with trees and those with bare ground or asphalt. In the March 2022 campaign,

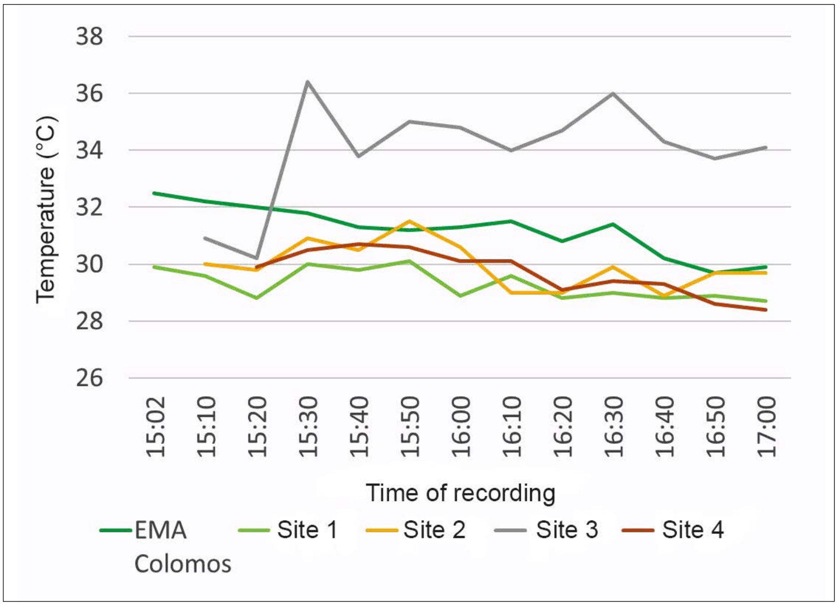


Figure 11. Average temperature records (°C) recorded at the sites shown in Figure 10 between 13 and 15 March 2022. Source: Own elaboration with data from the EMA Colomos stations and field records.

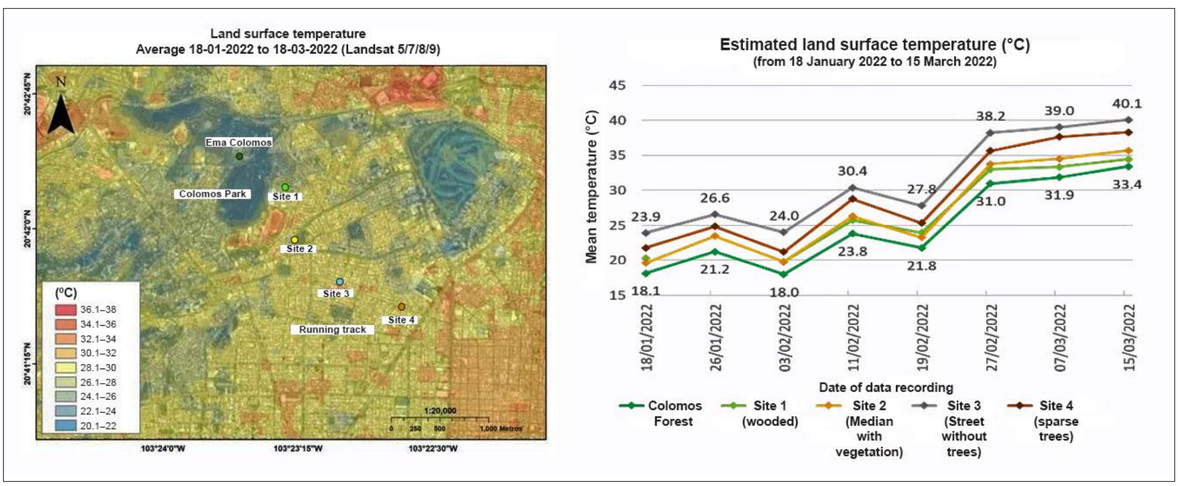


Figure 12. Estimation of soil temperature through Landsat images at sampling points. Source: Own elaboration with Landsat satellite imagery.

the ground temperature at the sites referred to was 6 °C higher in areas without vegetation than in wooded areas (Figure 12b).

DISCUSSION AND CONCLUSIONS

The green infrastructure of urban areas is a central factor in regulating the climate and, therefore, climatic comfort. The greenery and climate comfort analyses of GMZ highlight the importance of conserving at least a minimum of green infrastructure to maintain comfortable conditions, as recommended by international organizations. Unfortunately, in GMZ, 40 % of the neighborhoods lack the green infrastructure necessary to provide well-being conditions for their inhabitants.

Similar to other cities in Mexico, the urban model of GMZ for densely populated areas corresponds to one where the space is occupied mainly for houses and urban infrastructure with small areas for parks or gardens. This leads to less vegetation, intensifying the UHI and generating a greater climatic risk for more exposed people. In GMZ, 85 % of the green areas correspond to vegetation on public roads and sidewalks, which contributes to mitigating the UHI and improving air quality. However, given the conditions of urban infrastructure and its trends, climate regulation services have been declining.

To mitigate the UHI, the expansion of green areas through urban reforestation is considered an effective option since its regulation service allows reducing air temperature and regulating microclimate conditions. A study conducted in Shaoshan City showed that a 10 % increase in vegetation cover reduces the mean surface temperature by almost 1.5 °C (Agyemang *et al.*, 2019).

GMZ faces challenges in recovering green infrastructure. One way to recognize the value of the ecosystem services it provides is the hazards posed by heat waves. Under urban climate risk management and with an approach that considers the combined effect of other variables, it will be necessary to implement action strategies to counteract climate hazards and improve the environmental conditions and well-being of its inhabitants.

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