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Global Sustainability Science
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An Assessment on the Potential of Green Roofs in Seville, Spain, as a Strategy to Mitigate the Urban Heat Island Effect

Bachelor Thesis

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Summary

The urban heat island (UHI) effect is posing significant challenges to the thermal comfort and environmental quality of cities. This phenomenon arises with the nature of cities' architecture, that absorb most of the radiation and release it in the form of heat, causing urban areas to experience higher temperatures than the surrounding rural areas. The lack of vegetation cover in these areas and the global temperature rise expected with climate change only exacerbate the issue. This research was motivated by Seville's pressing need to address its extreme urban heat conditions, with the aim of evaluating the potential of green roofs (GRs) as a strategy to mitigate UHIs and promote urban sustainability.

A multi-criteria assessment was conducted using QGIS to determine the district in Seville that would benefit most from greening. This was based on population density, vegetation cover and land surface temperatures (LSTs). Two out of three indicators confirmed the presence of UHIs, as urban areas experienced higher LSTs compared to vegetated areas and water surfaces. This corroborated the cooling capacity of vegetation. Highly industrialized regions also exhibited significantly higher LSTs, reinforcing the role of intensive anthropogenic activities in exacerbating UHIs. *Macarena* was the selected district for further analysis as it experienced the highest population density, the lowest vegetation cover per capita, and moderate land surface temperatures. This decision maximized human benefit and addressed the critical deficits in vegetation.

The surface analysis in *Macarena* identified substantial opportunities for GR implementation, revealing that 74.3% (55.1 hectares) of roofs were suitable for greening in this district. Extrapolating this value to the whole city, 1,081.7 hectares of roofs were deemed suitable for greening, exceeding the 740 hectares needed to mitigate the temperature rise in the most adverse climate change scenario (6ºC). These findings provide a meaningful contribution to the research of Herrera-Gomez et al. (2017) and highlight the effectiveness of GRs as a strategy to mitigate the UHI effect in Seville, aiming to improve the liveability and sustainability of Seville.

1. Introduction

Urban areas are seeing rapid developments in recent years. More job opportunities, higher incomes, better education and health services are a major cause of increased rural to urban migrations, further driving urbanization (Selod & Shilpi, 2021). By 2050, 70% of the population is expected to live in cities (United Nations, 2023). In spite of their desirability, rapid urban development is associated with abrupt biodiversity losses, higher socio-economic inequalities and increased air pollution (Joshi et al., 2020). Cities are designed and built with materials that absorb most of the solar radiation and release it in the form of heat. These factors contribute to a phenomenon known as the urban heat island (UHI) effect (Herrera-Gomez et al., 2017). The global temperature rise associated with climate change is expected to aggravate this problem (Bauduceau et al., 2015; Joshi et al., 2020).

SDG 11 (Sustainable Cities & Communities) was established to address urban sustainability challenges, developing cities to become safer, more inclusive and resilient to global climate changes (United Nations, 2023). Nature-based Solutions (NBS) are often proposed as a solution to enhance human well-being, promote economic growth, and improve the environment (Bauduceau et al., 2015). Green roofs (GRs) are an example of this, consisting of green systems implemented at the roofs of buildings. They have demonstrated the capacity to reduce temperatures, provide thermal and noise insulation, and to increase the urban air quality and biodiversity, addressing major challenges associated with cities (Bauduceau et al., 2015; Herrera-Gomez et al., 2017; Joshi et al., 2020). For this reason, GRs have awakened interest as a solution to mitigate the UHI effect, ensuring urban areas remain resilient and sustainable in the face of environmental challenges. This is of particular concern in cities that already suffer high or extreme temperatures, such as Seville (Andalucía, Spain), a city located in the south of the Iberian Peninsula.

Seville experiences a unique thermal behavior within the Iberian Peninsula. This inland city has an average mean temperature of 19.1ºC. In the coldest months, average mean temperatures do not fall below 10ºC and from May through October, average temperatures of 20ºC are registered. In the summers, maximum average temperatures reach 35ºC, but it is also common to exceed 40ºC in the shade, reaching 50ºC occasionally. These high temperatures are a result of the warm and dry wind flow from Northern Africa's thermal lows (Capel Molina, 1975; WeatherSpark, n.d.). Herrera-Gomez et al. (2017) analyzed the climate change scenarios in the city of Seville and projected the temperatures to increase further by 1.5º to 6.5ºC by 2100. The thermal comfort of Seville could be deteriorated if no efforts are made to mitigate urban temperatures, putting into doubt the liveability and sustainability of the city.

Nevertheless, the central urban area was designed to adapt to these climatic conditions, also known as passive architecture (Borrallo-Jiménez et al., 2020). Characteristics of Seville's passive architecture include white washed houses to reflect solar radiation and narrow streets to maximize shading. Efforts to increase the shading of streets are also found in the form of canvas awnings covering streets or the plantation of trees, also benefiting from the cooling through evapotranspiration (Nikolopoulou et al., 2001).

Recently, Seville's municipality launched "Seville's Strategic Plan for 2030" (Ayuntamiento de Sevilla, 2019a). This includes the entire planning process regarding the future of the city, with sustainability as its core value. A key goal is to create a green city that mitigates and adapts to climate change by increasing the number of trees and green walls. For example, a regulation for this requires the planting of one tree species for every 20 m^2 in front of a new construction work. They also published a list of tree species aimed to be planted before 2030 in each district. Nevertheless, there was no mention of green roofs, raising the question about whether these efforts are sufficient to counteract the UHI effect and the predicted temperature rises.

A case study was conducted on the role of GRs in Seville, concluding that in the most optimistic climate scenario, 207 ha of GRs would be needed in the central urban area (11.3 % of the roofs) as a supplement to the existing green areas to mitigate the temperature rise associated with this scenario (1.5ºC). Conversely, 740 hectares (ha) would be needed to mitigate the temperature rise expected in the most adverse climate change scenario (6ºC) (Herrera-Gomez et al., 2017). This research assumed that GRs could be installed on all buildings and did not consider the height of buildings to have an effect, despite the published literature indicating the opposite. Generally, literature acknowledges the benefits GRs or vegetation could have on the UHIs, however, practical research assessing if these hectares are actually available is lacking. This knowledge gap is a key motivator of this study.

Being aware of the attributed benefits of GRs and their capacity to cool cities, the potential of existing roofs for greening in the city of Seville is an interesting solution to the UHI effect and foreseen temperature rises with climate change. In sight of this issue, this research will be guided by the following research question and sub-questions:

Research question: To what extent do roofs in Seville (Andalucía, Spain) demonstrate the potential for greening and contribute to a reduced urban heat island effect?

Sub-question 1: Which district would benefit most from greening?

Sub-question 2: How many hectares of roofs are available for greening?

This research aims to firstly, determine the district in Seville that would benefit most from greening based on a multi-criteria assessment. Then, to analyze the potential hectares of roofs for greening, looking at building type, height and surface characteristics, followed by an assessment of its capacity to reduce the urban heat island effect. Lastly, to assess how this contributes to urban sustainability.

2. Theory & concepts

This chapter describes the most relevant terms that have been used throughout this research.

2.1. Green Roofs & Greening

Green or living roofs are systems that integrate layers of soil and drainage to allow the successful establishment and growth of vegetation on roofs (see Figure 1). These roof systems are installed on top of the existing roof materials (e.g. asphalt or metal) if the conditions of the roof allow it, such as slope and the weight it can support. Smaller species can be established, usually making up lighter weight roofs that demand less substrate (extensive type). The intensive type can hold greater amounts of substrate, supporting small trees and shrubs. This type is more effective at reducing surface and ambient temperatures, but requires roofs with a greater weight load capacity (Herrera-Gomez et al., 2017).

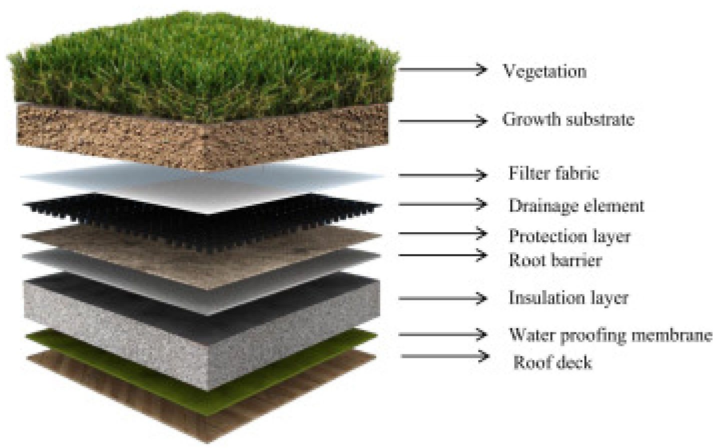

Figure 1: Simplified diagram of a green roof system and its components (Vijayaraghavan, 2016).

This study refers to *greening* as the process of increasing vegetation cover. Therefore, *the potential of roofs for greening* refers to the capacity to actively increase vegetation cover (grass, shrubs and/or trees) on roofs with the purpose of decreasing urban temperatures (Bowler et al., 2010; Herrera-Gomez et al., 2017).

In recent years, two green roof initiatives were launched in Seville. Completed in 2019, one of them incorporated 10,000 m^2 of extensive GRs in the newly built *Lagoh* shopping center, claiming to provide climatic, visual and well-being benefits. *Sedum* species were used, known for being drought-resistance and low maintenance. However, the roof was designed with a slope so an irrigation system was incorporated to aid maintenance (ZinCo Cubiertas Ecológicas S.L., 2019; see figure 2 below). The other project was opened to the public in 2023 as a recreation area, and is claimed to serve as a thermal insulator and increase energy efficiency. These 12,000 m^2 were also established on the roof of the new *TORRE Sevilla* shopping center and included a variety of species ranging from grass to trees (see figure 3; Diario de Sevilla, 2021; Torre Sevilla, 2023). No other green roof initiatives were found, indicating the novelty of this technology to the city of Seville.

Figure 2 & 3: Extensive GR on *Lagoh* shopping center and intensive GR on *TORRE Sevilla*. Retrieved from ZinCo Cubiertas Ecológicas S.L. (2019) and Sevilla21, (2023).

2.2. Urban Heat Islands (UHI)

UHIs are urban areas that have relatively higher temperatures than adjacent rural areas. This is a result of the positive thermal balance of cities, mainly caused by intensive anthropogenic activities and the high concentration of built structures. The lack of vegetation cover exacerbates the issue (Herrera-Gomez et al., 2017; Santamouris, 2014; Wong et al., 2003). The negative effects of UHIs include higher urban temperatures contributing to climate change and deteriorating thermal comfort conditions, increased energy demand of cities for cooling, intensification of pollution and higher rates of heat-related mortality. Overall, increasing the ecological footprint of cities (Santamouris, 2014).

This effect is present in all cities, however, its intensity varies for each city. Land surface temperature (LST) is often the indicator used to determine UHIs (Deilami et al., 2018). Jadraque Gago et al. (2020) analyzed the UHI effect in Seville by comparing the spatial and temporal patterns of LSTs from July of 1987, 2002 and 2017. The studied area included the city of Seville and its neighboring municipalities (consisting of impervious surfaces, arable land, grassland and shrubland areas). They found an average LST increase of 7.16ºC between 2002 and 2017, coinciding with the rapid rates of urbanization that occurred at this same time. Overall, the highest LST values were found in the central urban area of Seville, where construction materials and impervious surfaces are predominant, meaning a higher absorption of heat than the surrounding areas with vegetation cover (Jadraque Gago et al., 2020).

2.2.1. UHI mitigation through green roofs

Remote sensing technologies have been extensively used to determine the relationship between LST and vegetation cover in different cities. The normalized difference vegetation index (NDVI) is a tool used to determine the presence of vegetation. High NDVI values (>0.2) suggest the presence of healthy vegetation. Herrera-Gomez et al. (2017) found a negative correlation between LSTs and NDVI, indicating that areas with a high vegetation cover can lower LSTs due to the influence of evapotranspiration on the surface and shading (Ng et al., 2012). This indicates the potential of GRs to reduce air and surface temperatures, therefore, mitigating the UHI effect (Bauduceau et al., 2015; Joshi et al., 2020).

Bowler et al. (2010) conducted a literature review to assess the effectiveness of GRs to cool cities. They found two papers that suggested lower air temperatures above GRs and two papers that found no effect, but generally, lower surface temperatures were found on GRs as opposed to non-green. Another study assessing the spatial distribution of UHIs in Tel-Aviv, Israel, found that vegetated areas were the coldest elements within the city compared to other urban components (Saaroni et al., 2000). Another study in Japan found that urban areas with 30% of vegetation cover reduced urban air temperatures by 1ºC, and suggested that the urban greenery ratio in the central district should exceed this percentage (Ng et al., 2012). Additionally, a study conducted by Alexandri & Jones (2008) on the thermal effect of GRs and walls for various climates and urban landscapes concluded that vegetation cover in hotter and drier climates, such as that of Seville, has a greater effect on mitigating urban temperatures.

However, the efficiency of GRs at reducing ambient temperatures decreases with the height of buildings. A simulation study in Hong Kong examined the climatic effect of GRs at heights of 20, 40 and 60 meters. They found the effect of GRs on urban ambient temperatures at 60 meters to be negligible. For GRs installed at heights of 20 meters, the cooling effects found reached up to 0.6ºC, and 0.4ºC at 40 meters (Ng et al., 2012). Another study found that the efficiency of GRs at reducing LSTs increases with heights below 10 meters, indicating that in taller buildings, the effect of GRs will no longer be noticeable at street level, but will be at the roof level (Herrera-Gomez et al., 2017).

2.3. Sustainable cities & SDG 11

The concept of sustainability encompasses a broad range of interrelated factors, lacking a universally accepted definition. This gives rise to different interpretations, often adapted to the aim of the researcher (Tanguay et al., 2010; Turcu, 2013). The term was first coined in 1987 in the Brundtland report. Sustainability was then referred to as the balance between social, environmental and economic factors to "meet the needs of the present without compromising the ability of future generations to meet their own needs" (Tanguay et al., 2010).

When looking at indicators to measure urban sustainability, environmental indicators are often neglected (Tanguay et al., 2010). Green areas are an essential component of urban sustainability not only for the environment, but also for the social and economic dimension (Bauduceau et al., 2015; Joshi et al., 2020). Despite this consensus, there is no indicator arguing an increase in urban green areas as a means to achieve the targets of SDG11 (Sustainable Cities & Communities) (United Nations, 2023).

This research is motivated by the environmental dimension of sustainability by exploring the potential of increasing vegetation cover to reduce urban temperatures. This would also benefit the social and economic dimension by, for example, enhancing human well-being and reducing energy costs (Cheshmehzangi et al., 2021). Therefore, allowing the city of Seville to move closer to sustainability and become more resilient to the current and future challenges of climate change.

A conceptual framework has been designed to give an overview of the main concepts used and how they interrelate (see Figure 4).

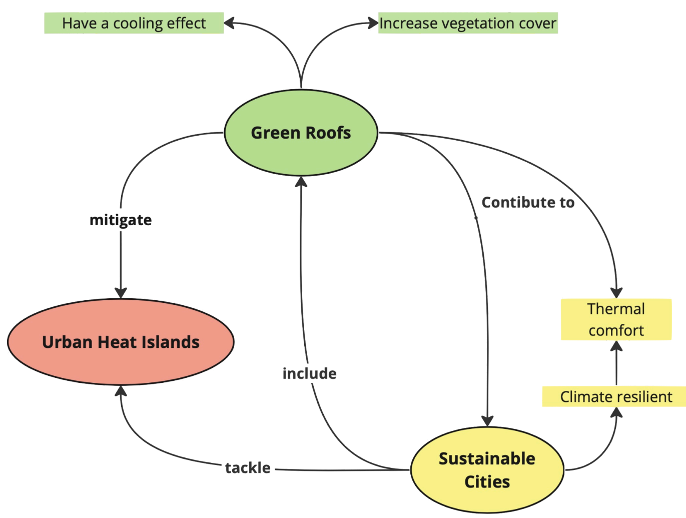

Figure 4: A conceptual framework to facilitate reader understanding (elaborated using Miro.com).

3. Material & Methods

This chapter elaborates on the data that was used and the methods performed to answer the research question. A multi-criteria assessment was conducted to determine which specific areas in Seville would better benefit from GRs, followed by a surface analysis of roofs in the determined area. Further description on the study area is also given.

3.1. Study area

Green areas make up 14% of the central urban area of Seville (Herrera-Gomez et al., 2017). With a population of 684.164 inhabitants in 2023, this is the highest total green surface area per capita in Andalucía (Instituto Nacional de Estadística, 2023). The existing green areas are widely dispersed, mainly found in the surroundings of the central urban area. The city center is almost completely paved with asphalt, making the installation of green areas difficult. These factors in combination with the climate make Seville highly susceptible to the UHI effect. The remote sensing analysis conducted by Jadraque Gago et al. (2020) found an average LST increase of 7.16ºC in the central urban area between 2002 and 2017, coinciding with the rapid urbanization rates.

3.2. Literature review

A literature review was conducted to help answer the research question, providing foundation of knowledge on the current situation and to guide the research design. Academic papers were the primary source of background information, accessed through Google Scholar, Scopus and Worldcat. Gray literature deemed relevant such as governmental and technical reports, graduate theses and newsletters were also used. Papers with a publication date earlier than the 2000s were excluded. There is one exception of a paper published in 1975 that examines the temperature profile of Seville over the course of a century (Capel Molina, 1975). This paper was compared to the temperature profiles of the past decade to assess if there have been notable changes in temperature. Search terms used include “rooftops”, “green roofs”, “urban heat island effect”, “urban heat mitigation”, “Seville”, “Andalucía”, “Spain”, “Urban sustainability”, and more. These search terms were combined with operators such as “AND” and “OR” to refine the scope. When a finding was highly relevant, backward and forward reference tracking was used. This will give insight on research from experts that are specialized in this topic, recent and past findings on the topic. To guide the methods, research was also conducted on solar panel potential of roofs, as this is a more researched topic and often follows a similar surface analysis.

Due to the lack of research on GRs in Spain, literature on the simulated and/or observed effects of GRs in other countries were also reviewed. To make external validations of this literature to the context of Seville and increase quality assurance, the findings will be assessed through triangulation. The key findings of the review were reported mainly in the introduction, theory &

concepts, methods and discussion chapters, to contextualize the relevance and findings of this research.

Figure 5 below gives an overview of the method that was followed to answer the main research question. The literature review contributed to every step of this research.

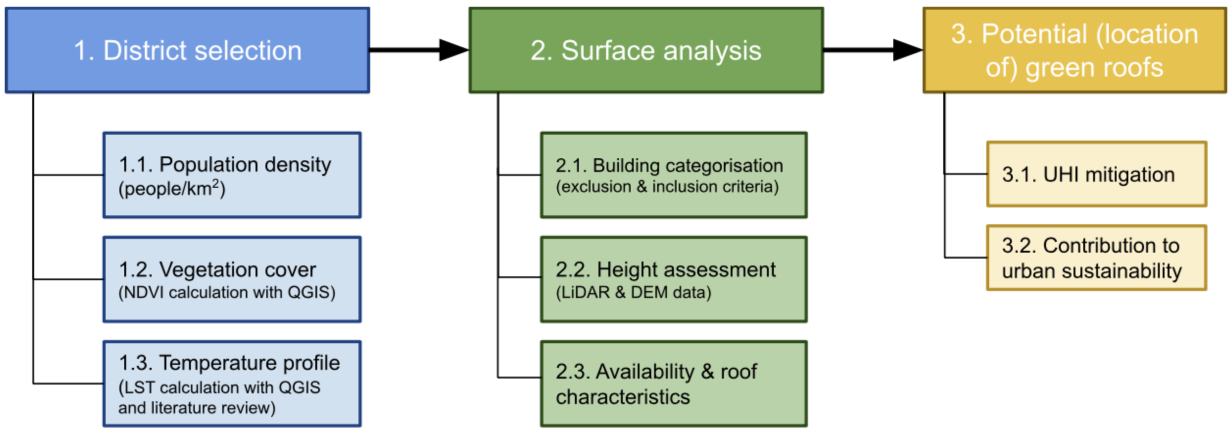

Figure 5: Analytical framework of the method's design based on and adapted from the methods designed by Velázquez et al. (2019) & Arcos-Vargas et al. (2019).

3.3.1. District selection

Firstly, the neighborhood that would benefit most from GRs in Seville was determined using a multi-criteria assessment adapted from Velázquez et al. (2019). This study presented a methodology to select the best location for the installation of GRs in large cities. They found neighborhoods located in the city center to be better suited for GRs as they have the highest ecological footprint in terms of pollution. The framework was adapted to the purpose of this study, as temperatures are a more concerning topic to the city of Seville. Therefore, the environmental conditions of different districts were compared by looking at the temperature profile, vegetation cover and population density. Ideally, the district with the highest population density, lowest vegetation cover (NDVI) and highest temperatures (LSTs) was selected. A trade-off analysis was necessary as no district achieved the ideal criteria.

The most recent population data (1/01/2024) and area (km^2) of each district has been retrieved from the *Ayuntamiento de Sevilla* (2024), an official spanish website from the municipality of Seville. From this data, population density (people/km^2) was calculated to make comparisons between the populations of different districts and understand how the population is dispersed.

Vegetation cover data was retrieved from a combination of sources. Namely, NDVI was calculated using QGIS from Landsat 8 satellite imagery retrieved from the USGS Earth Explorer

(2023). See Appendix A for a detailed overview of procedure. Literature argues NDVI values greater than 0.2 to be considered healthy (Herrera-Gomez et al., 2017). For this research, NDVI values greater than 0.15 were also classified as vegetation because when comparing the NDVI map (30 meter resolution) to high resolution (2.5 meters) orthophotos, trees and other vegetation types were observed in areas where the NDVI was below 0.2. Using QGIS, NDVI results were then translated into the percentage of vegetation cover for simplification. Additionally, the Agenda 2030 for Seville and open data on the parks and vegetation cover for each district published by *Ayuntamiento de Sevilla* (2019) and *Junta de Andalucía* (n.d.) respectively, were reviewed to assess current and future greening efforts.

To identify the UHI's in Seville, LSTs were determined by processing algebraically Landsat 8 imagery in QGIS (See Appendix A) for two different years during the same month (September 2013 & 2023). This data was also retrieved from the USGS Earth Explorer and was processed following the method published by Avdan & Jovanovska (2016). Schwarz et al. (2011) conducted research on indicators that can be used to quantify UHIs in European cities. They found 11 UHI indicators for remote sensing data. Three indicators were used to validate the existence and spatial distribution of UHIs in Seville, given the data available for this research. A LST difference map between both years was also elaborated (see Appendix B), however, the differences in the climatic conditions of each year obscure the presence of UHIs. Therefore, LSTs for both years were assessed separately.

3.3.2. Surface analysis

After having selected the district that would benefit most from GRs, an analysis on the roof surface area suitable for greening was conducted. This was based on the methods of Arcos-Vargas et al. (2019). Their research consisted of identifying the solar energy potential of roofs in Seville to become self-sufficient, and their methods were designed using publicly available data. In their research, they analyzed a random sample of residential and industrial roofs in Seville through photo-interpretation and then extrapolated the availability of these roofs to the rest of Seville to determine the solar potential. According to a sample of 8 residential roofs, they found a mean availability factor of 68% for flat residential roofs. Given the population size and variability of the buildings in Seville, this research argues a larger sample size is needed for a more accurate extrapolation.

Firstly, geographical information on the building footprint was downloaded from *Instituto Geográfico Nacional* (2020) and *Ayuntamiento de Sevilla* (n.d.), both being official spanish websites from the government of Spain and the municipality of Seville respectively. The SIOSE-AR database retrieved from *Instituto Geográfico Nacional* (2020) provides high resolution information on the land occupation information in Spain, building cover and roof surface area (SA). B.I.C and SIOSE-SI databases were also used as they provide geographic information on the registered assets of cultural interest and industrial floor use respectively, retrieved from *Ayuntamiento de Sevilla* (n.d.) and *Instituto Geográfico Nacional* (2020). Using QGIS, the buildings were categorized into types, mainly based on their use. Missing data was revised and adjusted through photo-interpretation of orthophotos from USGS (2020). Following, a map was computed with the purpose of categorizing buildings into the following types:

- Maily residential (residential, educational, hospitals, etc.)
- Industrial
- Commercial
- Monuments
- Belonging to historic complex
- Educational ground (shows delimitation of educational ground)
- Sports field
- Community use (open spaces, urban parks, parking lots, churches, etc.)

Then, a cartographic analysis was conducted to identify how many urban elements fall under each category. Buildings that fall under the type 'community use' and 'sports field' were excluded from further analysis due to their structural and functional limitations to GR implementation. Additionally, current urban planning regulations do not allow 'monuments' to be expanded or altered in any way. This building type was also excluded from further assessment if it was found in the selected district.

When it comes to buildings 'belonging to historic complex', regulations only allow modifications that preserve the aesthetic of the buildings, given that the texture and color do not cause significant visual disruption or impact. The official urban planning regulation document published by the Ayuntamiento de Sevilla (2007) stated that roofing materials of transitable and non-transitable roofs in these buildings should correspond to pressed brick, in traditional ocre, brown, and straw tones. Concrete and floating wooden roofs are permitted. Visible waterproof fabrics, reflective aluminum sheets or similar materials are not allowed under any circumstances. The implementation of GRs does not comply with these regulations, therefore, this building type was excluded from further analysis.

Following, elevation models (2.5m resolution) published by *Instituto Geográfico Nacional* (2020) were downloaded to retrieve the height of buildings. This study excluded all buildings higher than 40 meters with the purpose of identifying roofs that could still have an effect on temperatures at street level (Ng et al., 2012). Buildings of all heights should be considered if the purpose of implementing GRs were to improve air quality or promote biodiversity, among other benefits.

For the installation of GRs, flat roofs or roofs with a slope below 10º are optimal (Arcos-Vargas et al., 2019). Due to the lack of publicly open data on roof surface characteristics, satellite imagery was used to determine the availability of the selected roofs based on the methods implemented by Arcos-Vargas et al. (2019). For this research, a sample size of 10% of 'mainly residential' roof surfaces in the selected district was analyzed, consisting of 308 rooftops, in addition to 14 'commercial' buildings (100%) and one 'industrial' building (100% in this district). The purpose of this was to increase the validity of the extrapolation and substantiate the percentage of flat residential roofs available determined by Arcos-Vargas et al. (2019). In order to be considered suitable for greening, roof characteristics must meet the following criteria:

- Flat roof
- Have access to sunlight
- Unoccupied for other purposes (e.g. no solar panels or swimming pools)

From the random sample determined using QGIS, roofs that did not meet the above criteria were excluded (see Appendix D for roof examples). The sum of the surface area (SA) of the remaining roofs in the sample was calculated and converted into a percentage of the total sample. This percentage was then used to estimate the hectares available for greening in the selected district. To extrapolate the results of *Macarena* district to the city of Seville, the sum of all roof's SA in Seville was calculated using QGIS from all 'industrial', 'commercial' and 'mainly residential' buildings in the city. The resulting value was then multiplied by the percentage factor of suitable roofs for greening in the *Macarena* district to estimate the roofs available for greening on the city-wide scale.

4. Results

4.1. Selected District

A multi-criteria assessment on population density, vegetation cover and LSTs was conducted to identify which district would benefit most from GRs. The results are as follows:

4.1.1. Population density

Population statistics and the area of each district has been recorded in a table and a new column has been added in bold to indicate the new contribution, as shown in Table 1.

Table 1: Population data and area of the districts in Seville. Data retrieved from Ayuntamiento de Sevilla (2024) and Ayuntamiento de Sevilla (n.d.).

District	**Population (2024)**	**Area (km²)**	**Population Density (people/km²) 2024**
Bellavista- La Palmera	42,647	16.04	**2,659**
Casco Antiguo	56,980	4.23	**13,470**
Cerro-Amate	90,913	7.50	**12,122**
Este	107,133	31.38	**3,414**
Los Remedios	25,771	15.56	**1,656**
Macarena	76,059	3.17	**23,993**
Nervión	51,276	3.20	**16,023**
Norte	70,963	38.57	**1,839**
San Pablo-Santa Justa	59,018	5.63	**10,483**
Sur	69,359	7.49	**9,260**
Triana	47,114	9.32	**5,055**

Table 1 shows that *Este* is the district with the highest population. Nevertheless, it appears to have one of the lowest population densities. Conversely, the population density of the *Macarena* is comparatively higher than that of any district, surpassing the second most densely populated district by 7,970 people/km^2. See figure 6 below for a visual overview of the population's distribution.

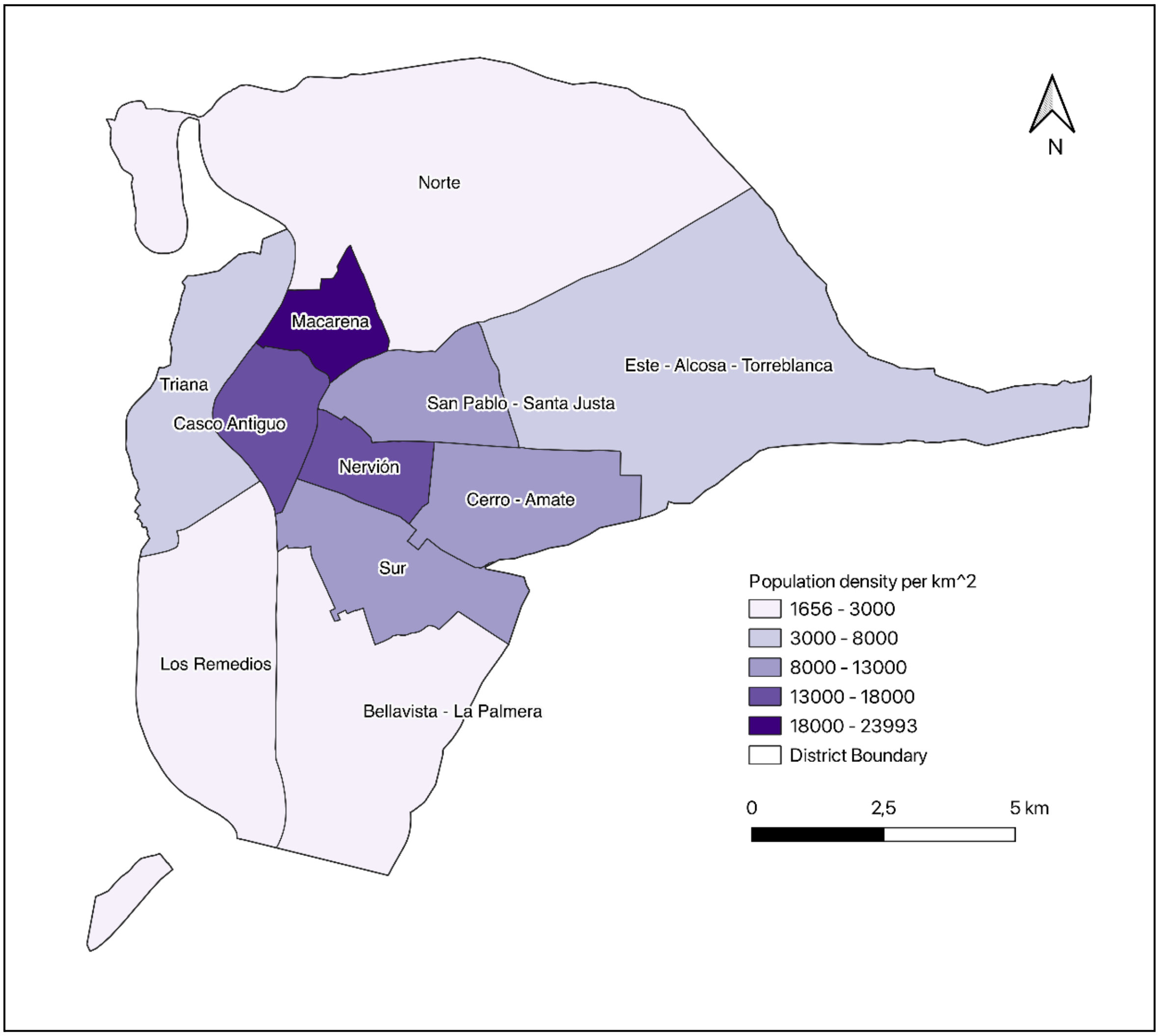

Figure 6: Population density per km^2 in each district of Seville.

Figure 6 shows that the most densely populated districts are clustered around *Casco Antiguo,* the oldest district of Seville. It is evident that *Macarena* is the most densely populated district, indicating more people would benefit from greening in this district.

4.1.2. Vegetation Cover (NDVI)

This section assesses the extent of vegetation in each district based on NDVI and its translation to percentage of vegetation cover.

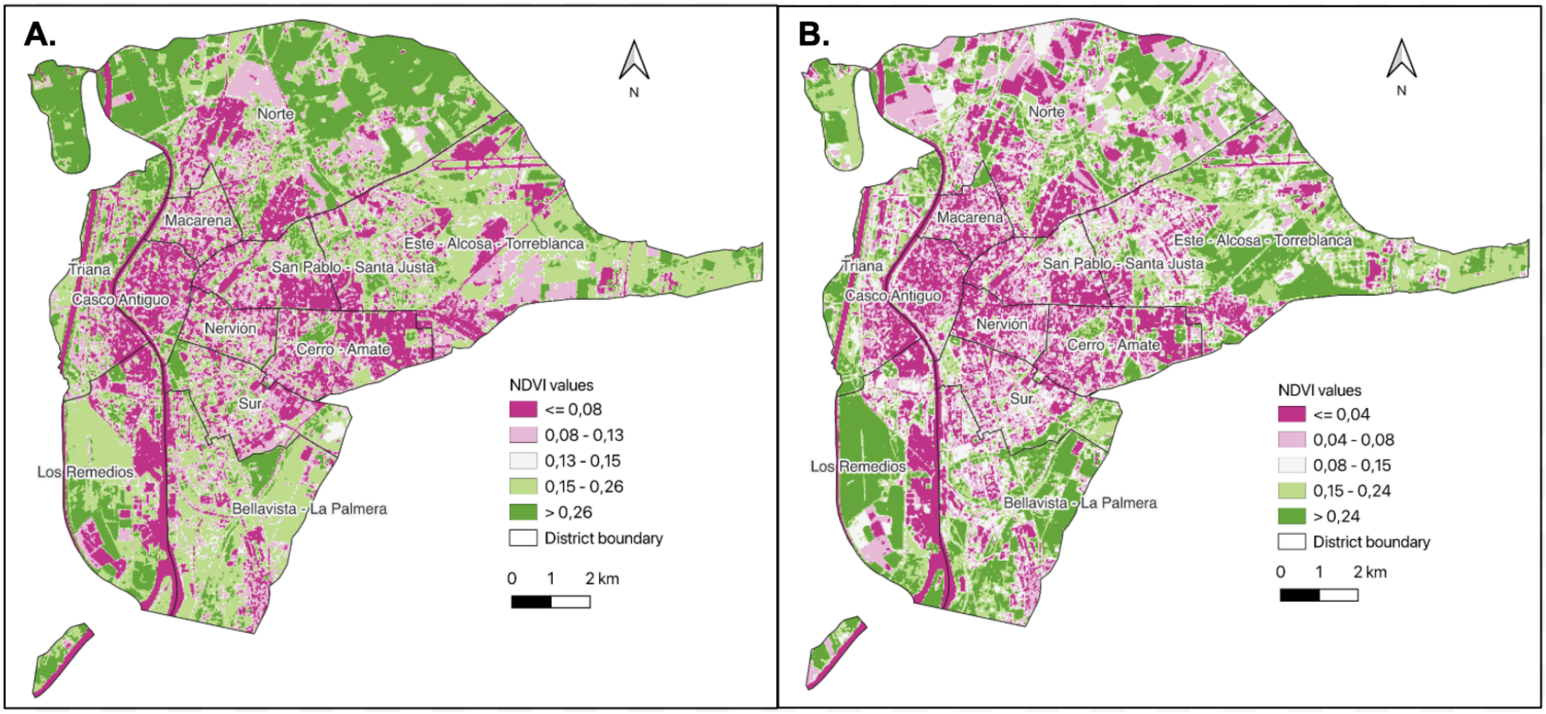

Figure 7: NDVI map of Seville for **A.** 2013; and **B.** 2023. Calculated by processing algebraically Landsat 8 imagery from USGS (2023).

Figure 7 shows that the central districts have the lowest NDVI values, indicating a low vegetation cover. Green patches can be observed within these districts, revealing the presence of urban parks, however, this remains a minority. Conversely, the surrounding districts have higher NDVI values, illustrating the presence of more vegetation cover and less urbanization. Table 2 presents relevant information calculated to identify the areas with lowest and highest vegetation cover.

Table 2: NDVI values in km^2, as a percentage of vegetation cover and as vegetation per capita. Data retrieved from USGS (2023) and then processed algebraically using QGIS.

District	District area (km^2)	**Area of NDVI>0.15 (km^2)**	**Percentage of vegetation cover (%)**	**Vegetation per capita (m^2/person)**
Bellavista- La Palmera	16.04	**9.71**	**60.60**	**233.2**
Casco Antiguo	4.23	**0.33**	**23.64**	**5.6**
Cerro-Amate	7.50	**1.68**	**22.40**	**19.0**
Este	31.38	**20.94**	**66.73**	**200.9**
Los Remedios	15.56	**7.74**	**49.74**	**304.2**
Macarena	3.17	**0.34**	**10.73**	**4.6**
Nervión	3.20	**0.27**	**8.44**	**5.3**
Norte	38.57	**18.10**	**46.93**	**245.3**
San Pablo-Santa Justa	5.63	**1.15**	**20.43**	**18.9**
Sur	7.49	**2.45**	**32.71**	**34.5**
Triana	9.32	**4.21**	**45.20**	**86.7**

The table shows that the district with the highest vegetation cover is *Este* (66.73%) followed by *Bellavista* (60.60%), whereas *Los Remedios* has the highest vegetation per capita (304.2 m^2/person). Agricultural fields were also included as vegetation cover, mainly present in the districts *Norte, Este, Los Remedios* and *Bellavista*, which partly explain their high vegetation cover. *Nervión* is the district with the lowest vegetation cover *(*8.44%), however, *Macarena* stands out for having the lowest vegetation per capita (4.6 m^2/person). While the district *Casco Antiguo* seems to have relatively high vegetation cover (23.64%), its vegetation per capita also stands out for its low value (5.6 m^2/person).

4.1.3. Temperature Profile

The following section explores the land surface temperatures of 2013 and 2023 (see figure 8) as an indicator of UHIs in Seville (see Appendix B for the LST difference map).

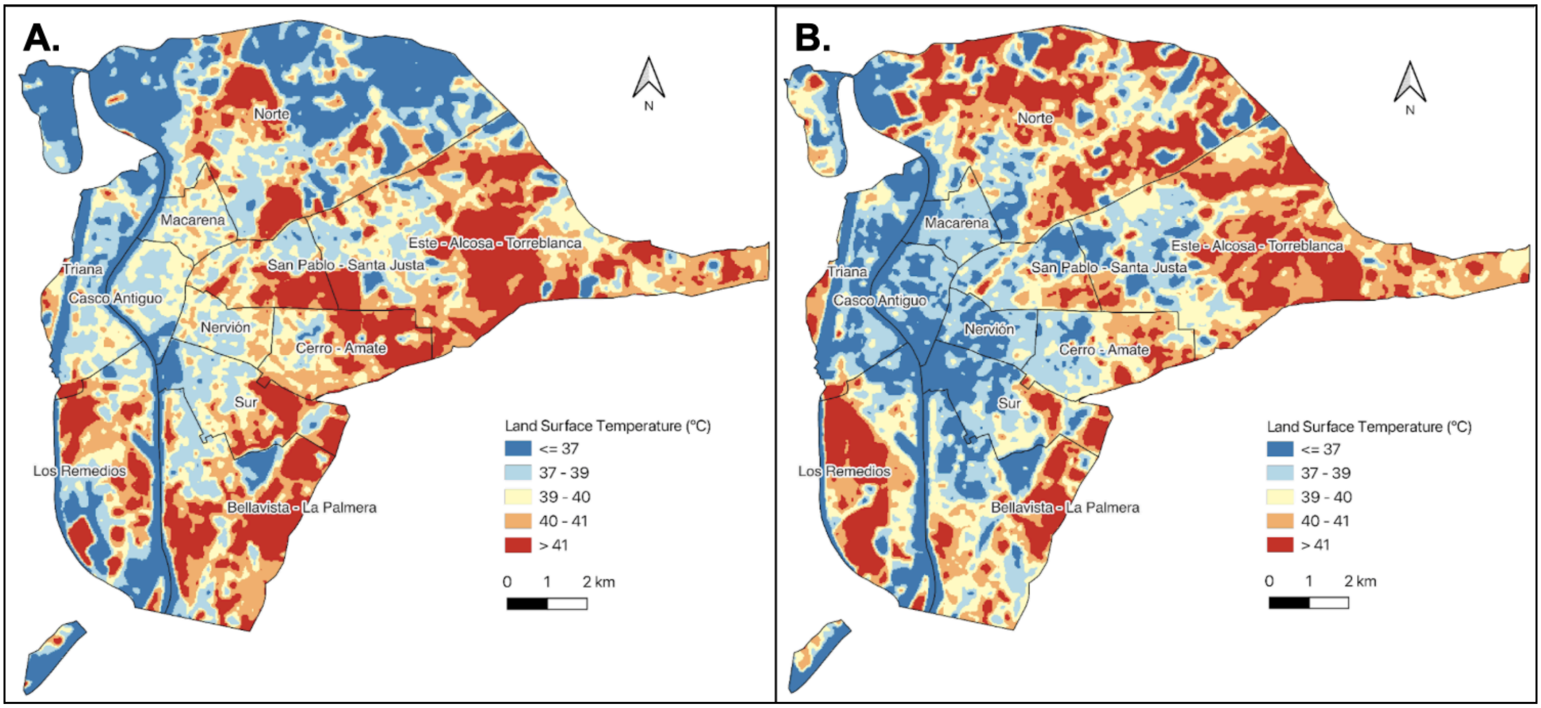

Figure 8: LSTs in the city of Seville in **A.** September 2013 and **B.** September 2023. Calculated by processing algebraically Landsat 8 imagery from USGS (2023).

The figure above shows LSTs are higher in the surrounding districts, in particular the regions with cropland (*Norte, Este* and *Bellavista*). The indicator stated by Schwarz et al. (2011), which assesses the temperature difference between urban areas and cropland, would suggest UHI are not present in Seville. Two other indicators suggest the opposite. One indicates UHIs to be true if there is a difference in the LST of urban and water surfaces (Schwarz et al., 2011). In 2013 (A.), it is evident that the LST of the river (<37ºC), which can be seen in figure 8 as a dark blue line separating *Casco Antiguo* from *Triana,* was significantly lower than the rest of the city. This was also true for 2023. Another indicator states that UHIs are present when there is a difference in the mean LST between urban areas and all other areas, including vegetation in urban areas (Schwarz et al., 2011). When comparing figure 8 with figure 7 (NDVI map), it becomes clear that most regions within the central urban area that have a high NDVI, also experience lower LSTs. An example of this can be seen at the south of *Casco Antiguo,* where the largest park in Seville is found, *María Luisa Park,* consisting of 34 hectares (Ayuntamiento de Sevilla, 2023). Additionally, *San Pablo-Santa Justa* district experiences significantly high temperatures (>41ºC), coinciding with the agglomeration of industrial buildings.

A table including the mean LST increase from 2013 to 2023 in each district can be found in Appendix B. The LST increase in the central districts ranges from 0.37 ºC to 1.42ºC. This is significantly low compared to the 7.84ºC and 5ºC increase in *Norte* and *Este* respectively, the districts with the highest extent of agriculture.

Given that no district achieved the ideal criteria for selection (highest population density, lowest vegetation cover (NDVI) and highest temperatures (LSTs)), a trade-off analysis is necessary. The QGIS analysis revealed that the *Macarena* district has the highest population density and lowest vegetation per capita, scoring highest on two out of three criteria. Although the LSTs for this district are lower than surrounding (e.g. *Norte*, *Este*, *Los Remedios* and *Bellavista*), figure 8 depicts that UHIs are also present in this district, experiencing temperatures up to 4ºC warmer than water surfaces and vegetation. This supports the use of GRs in *Macarena* to mitigate UHIs.

4.2. Surface Analysis

The following section presents the results of the surface analysis in *Macarena* district.

4.2.1. Building Categorisation

This section gives an overview of the building types present in *Macarena*; see Figure 9. This figure has been analyzed to see which buildings are suitable for greening.

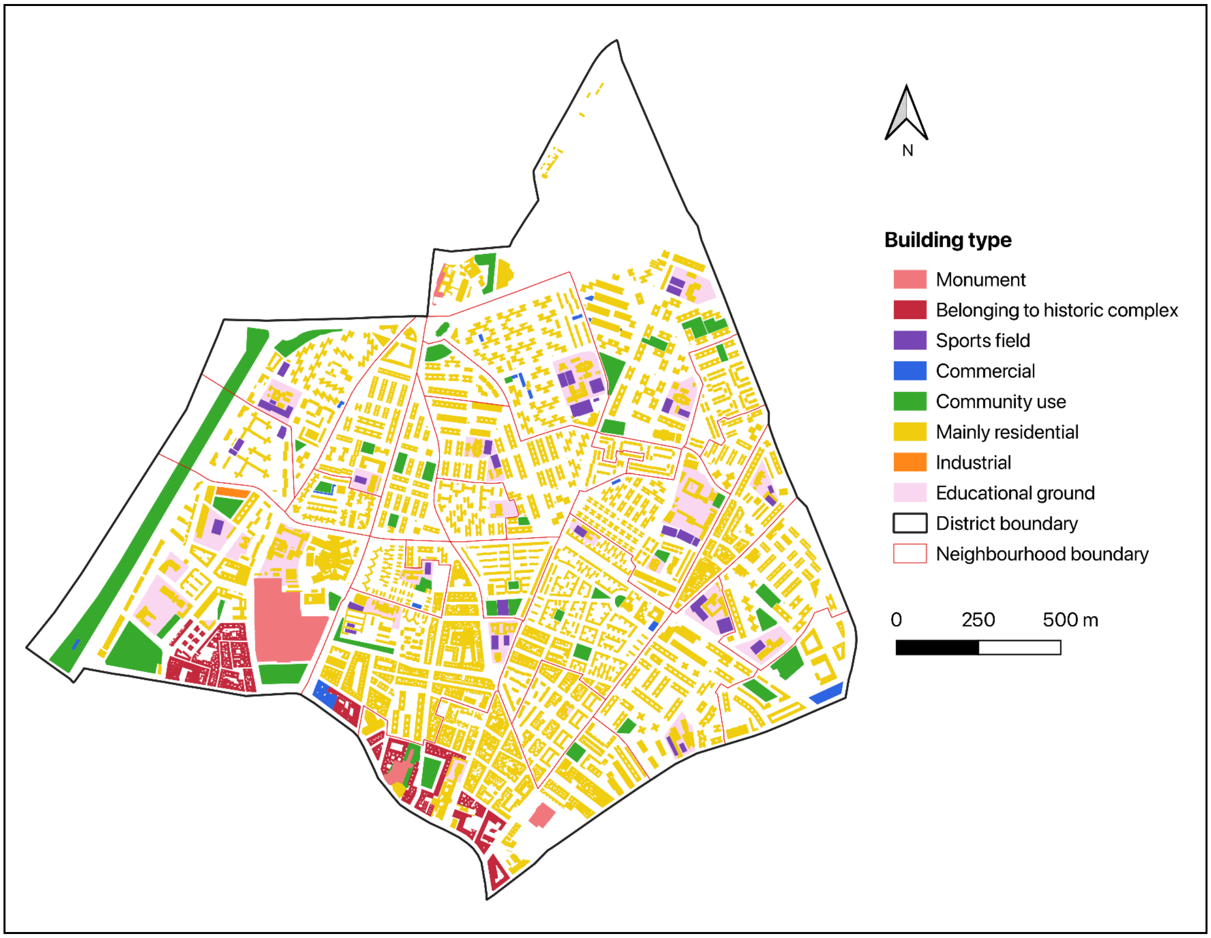

Figure 9: Map created from the SIOSE-AR (Instituto Geográfico Nacional, 2020), SIOSE-SI & BIC (Ayuntamiento de Sevilla, n.d.) datasets to portray the use given to each building in the district *Macarena*.

'Mainly residential' buildings are prevalent in this district, consistent with the fact that it is also the most densely populated. This category includes hospitals and buildings within 'educational ground', which were combined due to their similar roof characteristics. 'Commercial' buildings are also scarce but like the 'mainly residential' type, they are characterized by flat roofs, therefore, will also be included for further analysis.

Assets of cultural interest ('monuments' and 'belonging to historic complex'), 'community use' buildings and 'sports field' were also found in this district. As mentioned in the methodology, these buildings will not undergo further assessment.

4.2.2. Height Assessment

The height assessment was conducted to exclude buildings above 40 meters; see figure 10 for a display of building height.

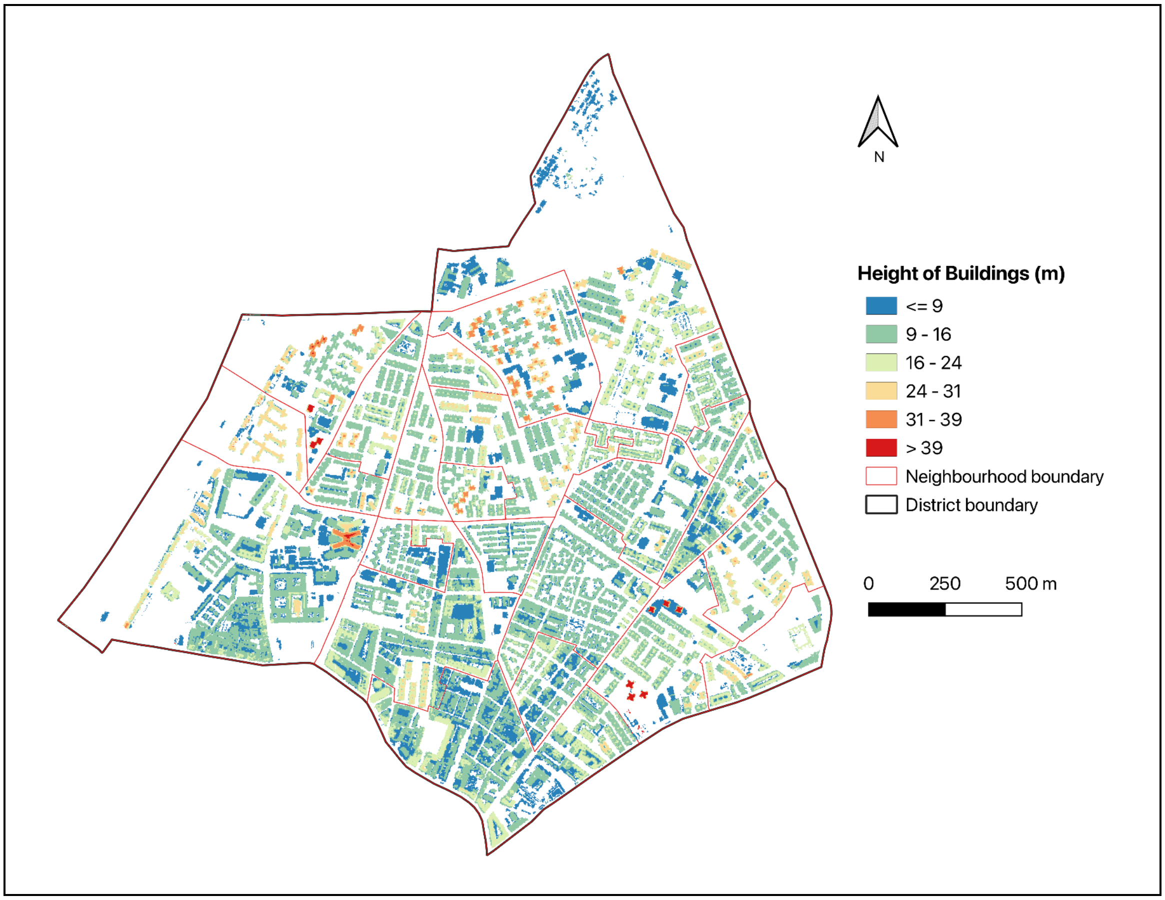

Figure 10: A map to visualize the height of buildings in the *Macarena* district.

The height assessment indicates that most buildings in *Macarena* district have a height below 40 meters. The maximum height of a building in this district was 46 meters. Only 0.3% (2.45 ha) of the buildings are taller than 40 meters. These are depicted in red in the figure above. These buildings are excluded from further assessment. Additionally, 78.5% (576,618 ha) of the 'residential' buildings have a height equal to or below 20 meters. All 'commercial' and 'industrial' buildings have a height below 20 meters.

4.2.3. Roof Suitability

This section presents the results from the roof surface analysis of a random sample of buildings remaining after the height assessment and building categorisation. From this sample, only the buildings that met the suitability criteria mentioned in section 3.3.2 were deemed suitable for greening (see Appendix D for examples). This study excludes other considerations such as the structural weight capacity of roofs. See results displayed in table 4.

Table 4: Total roof surface area (SA) of buildings compared to the surface area suitable for greening using QGIS data and photo-interpretation.

Building type	Total roof surface area available (m^2)	Roof surface area suitable for greening (m^2)	Percentage (%) suitable roofs of total roof surface area
Industrial	2349	956	40.7
Commercial	7582*	3559	46.9
Mainly Residential	731,875*	546,711	74.7
Sum	741,806	551,226	74.3
Sum Equivalent in hectares (ha)	74.2	55.1	74.3

*One of the commercial buildings was not registered in the QGIS data sets as it was constructed after 2017. No information could be retrieved on the roof SA, however, from photo-interpretation it was observed that this roof is already occupied by solar panels. This building has been excluded from the table above. This was also true for 8 residential buildings.

For 'industrial' buildings, 2349 m^2 of the total roof surface area (SA) is suitable for greening, while for 'commercial' buildings it is 7582 m^2. Industrial buildings tend to have pitched roofs (Arcos-Vargas et al., 2019), which was the reason why only 40.7% were deemed suitable. For commercial buildings, "occupied for other purposes" was the underlying reason for only 46.9% being suitable out of 14 roofs analyzed. Nevertheless, the number of 'industrial' and 'commercial' buildings is too low in the *Macarena* district to make valid assumptions or extrapolations with these percentages. On the other hand, 'mainly residential' buildings show the highest suitability, with 74.7% of the total roof SA (731,875 m^2) suitable for greening. This was based on a sample of 308 roofs (excluding buildings above 40 meters; see Appendix C for an overview of the sample). Occupied for other purposes, pitched roofs and access to sunlight were all reasons for exclusion, leaving 245 roofs appropriate for greening. Overall, 74.3% of the assessed roof SA is suitable for greening in the *Macarena* district, equivalent to 55.1 hectares. This translates into 17.4% of the area of *Macarena*. Combined with the existing hectares of vegetation in this district (34 ha), this would be equivalent to 28.1% of the area of *Macarena*.

The results presented in table 4 were then used to estimate the potential for GRs in the city of Seville. The sum of all roofs' SA excluding assets of cultural interest, sports fields, and buildings above 40 meters resulted in 14,585,308 m^2 (see Appendix E for more detail). When multiplied by the percentage factor of suitable roofs in *Macarena*, 10,817,095 m^2 of roof surface was deemed available. This is equivalent to 1081.7 hectares of roof SA suitable for greening in the city of Seville, meaning 7.6% of the area of Seville would be covered with vegetation only from green roofs.

5. Discussion

The population density analysis revealed significant differences among the districts. The surrounding districts have the lowest population densities due to their large areas, despite having the highest absolute population. Conversely, *Macarena* was the district with the highest population density due to its small area. The NDVI analysis suggested that the most densely populated districts also exhibit the lowest NDVI values, indicating the trade-off between vegetation cover and population density (McDonald et al., 2023).

One out of the three indicators used to measure UHIs, showed no UHIs are present in Seville (Schwarz et al., 2011), as croplands experienced higher LSTs compared to urban areas. This could be explained by the climatic conditions of each year; 2023 was a hotter and drier year compared to 2013 (see Appendix B; Tutiempo Network, 2024b). It is likely that croplands experienced drought and bare soil was exposed. Jadraque Gago et al. (2020) found that bare soils have a higher LST than vegetation, and often higher than asphalt. Nonetheless, two out of three indicators confirmed the presence of UHIs. One of them, which compared urban areas to vegetation (e.g. urban parks), was supported by comparing the NDVI map (figure 7) with the LST map (figure 8). Areas that experienced lower LSTs generally coincided with high NDVI values, corroborating the capacity of vegetation to reduce temperatures (Alexandri & Jones, 2008; Herrera-gomez et al., 2017; Ng et al., 2012). These findings further support the implementation of GRs in Seville. It was interesting to find that the highly industrialized area in *San Pablo-Santa Justa* district also experienced significantly higher LSTs compared to residential areas, supporting that UHIs are enhanced by intensive anthropogenic activities (Santamouris et al., 2014; Wong et al., 2003). Surprisingly, the average LST increase from 2013 to 2023 (Appendix B) was also significantly low (from 0.37 ºC to 1.42ºC) compared to the 7.16ºC increase in the central urban area found by Jadraque Gago et al. (2020) between 2002 to 2017. This could be explained by the decrease in the rates of urbanization. In fact, Seville aimed to stay above 700,000 inhabitants. Despite its rapid urbanization since the late 1900's, 2014 was the first year to fall under the target population, halting the rapid urban development that could explain the LST increase from 2002 to 2017 (Rodriguez, 2023).

When comparing the LSTs of any urban area to that of water surfaces or vegetation, UHIs are present in all the districts of Seville. For this reason, the trade-off analysis supported the selection of the *Macarena* district given its high population density, low vegetation cover and moderate UHIs. This decision maximizes human benefit and addresses the critical deficits in vegetation. In fact, the municipality of Seville has already established plans to improve the quality of the urban environment in *Macarena*, as it is one of the districts encountering the most urban and environmental challenges. One way in which they aim to achieve this is by increasing the abundance of natural resources and diminishing noise pollution (Ayuntamiento de Sevilla, 2019).

GRs also demonstrate the potential to achieve this goal as they provide noise insulation and enhanced air quality, further supporting their implementation in this district (Zhang & He, 2021).

The surface analysis in *Macarena* highlighted a substantial opportunity for GR implementation. The majority of buildings in *Macarena* were below 20 meters. Based on the study by Ng et al. (2012), this indicates GRs will have a significant effect on temperatures at pedestrian level, contributing to thermal comfort and mitigating the UHI effect. The random sample of 323 roofs analyzed by photo-interpretation revealed that approximately 74.3% (55.1 ha) of the roofs were suitable for greening. The implementation of GRs within *Macarena* in addition to the existing vegetation in this district would make up 28% of the vegetation cover. Ng et al. (2012) also found that urban areas with 30% of vegetation cover reduced urban air temperatures by 1ºC, indicating GRs to be a promising path to increase the thermal comfort of this densely populated district.

The extrapolation to the city of Seville resulted in 1081.7 hectares of roof SA suitable for greening, which would entail a 7.6% of the area of Seville. Remarkably, the hectares of roofs available for greening in Seville exceed the minimum hectares needed (740 ha) to mitigate the temperature rise expected in the most adverse climate change scenario (6ºC). Herrera-Gomez et al. (2017) made the assumption that GRs could be installed in all buildings, without considering height or structural and functional limitations. After addressing the majority of these limitations, this research still found green roofs to be an imperative strategy for the mitigation of the UHI effect, significantly contributing to the liveability and sustainability of the city.

5.1. Limitations of research

The resolution of the data used plays an important role in the accuracy of the findings. For example, the NDVI was derived from Landsat 8 imagery with a 30 meter resolution. This resolution does not accurately capture small vegetation patches, or individual trees in the streets of Seville. This could lead to an overestimation or underestimation of the actual vegetation cover found in Seville. Even so, this resolution was valuable to assess the general vegetation cover.

The benefits of croplands differ from those of natural vegetation; temperature reduction being one of them (Jadraque Gago et al., 2020). A limitation of this study was classifying croplands as vegetation cover, assuming the same benefits of healthy vegetation. Instead, they consisted mainly of bare and dry soils causing an increase in the LSTs and obscuring the UHI effect. Nonetheless, both years were assessed separately to identify common patterns on the spatial distribution of UHIs and vegetation cover.

This research assumed climatic conditions of Seville would be able to sustain green roofs, given the existing research on drought-resistant and low maintenance species that have been implemented on green roofs. Alexandri & Jones (2008) also indicated that vegetation cover in hotter and drier climates has a greater effect on mitigating urban temperatures. Nonetheless, it is important to consider the extreme conditions that the city can experience. Although the mean annual temperature of the city of Seville suggests its adequacy for GR implementation, extreme temperatures should be considered when designing suitable systems (Hopkins & Goodwin, 2011). In addition, the suitability criteria did not address the weight load capacity of roofs. This was also a limitation of Herrera-Gomez et al. (2017). The estimation on the hectares of roofs available would need to be verified by calculating how much weight they can support.

Another major limitation is that the surface analysis was limited to the *Macarena* district, providing valuable insights for this area. Other districts in Seville have different urban characteristics, therefore, the findings may not be fully generalizable. Expanding this study to multiple districts would provide a more comprehensive understanding on the potential of roofs for greening in the city of Seville.

It was not always possible to validate relevant literature through triangulation before making extrapolations to Seville due to the lack of research on the quantitative effects of GRs. However, this study was grounded on peer-reviewed qualitative research and empirical research on similar climatic conditions to that of Seville. The findings of this research provided new context-specific insights and aligned with existing literature that underscores the efficacy of green roofs in mitigating UHIs.

5.2. Policy recommendations

Despite GRs being a novel technology in Seville, the two projects launched in the past years underscore the city's commitment to urban innovation and sustainability. Therefore, it is essential to think about how to persuade users to implement, use and maintain GRs, in order to maximize the benefits of roofs and contribute to the city’s goals.

Compulsory policies, including regulations and standards, are the most rigorous way to achieve city-wide GR implementation (Zhang & He, 2021). For example, by mandating that a certain percentage of the roof area in a new building needs to include GRs, such as the recent regulation for solar panels (Pérez Urrestarazu, 2018). This policy approach promotes sustainable urban development and can serve as an example to gain interest among residents. Collaboration between policymakers and urban planners is also recommended to promote green infrastructure in Seville, such as more urban parks, gardens and green walls, to work in synergy with GRs.

Incentives and guidance from the government are also essential. For example, financial incentives such as subsidies, can also encourage community investments in this technology (Zhang & He, 2021). In Seville, it is common to find residential buildings with shared ownership of roofs. Sharing the costs of the GR might also motivate residents to participate. However, the use that is given to the roofs must be agreed upon among the community of owners living in that building (Centeno, 2023). To promote GRs in such buildings, it is important to implement governmental policies that can inform the residents on the benefits GRs would bring, such as increased property value, energy savings, increased air quality, localized cooling and enhanced well-being (Cheshmehzangi et al., 2021). It is also important for the GRs to be accessible to the residents of the buildings, in order to maximize the benefits on residents' well-being and encourage community engagement.

5.3. Recommendations for future research

While simulation studies have estimated the effect of green roofs on buildings of varying heights, empirical research is necessary to validate these findings. This will enhance the accuracy of predictions, providing a more reliable estimation on the impact of GRs in the city of Seville. To complement this study, it is recommended for future research to assess the structural load capacity of roofs that are suitable for greening. It is also crucial to analyze the social and economic barriers to GR in Seville.

Several studies suggest *Sedum* to be a resilient plant species in hot and dry climates, similar to that of Seville (Bousselot et al., 2011; Castleton et al., 2010; Farrell et al., 2012). These require low maintenance and are resilient to drought periods. It is essential to carry out experimental research on which species would be most suitable to implement, as the type of green roof (extensive or intensive) will have a different effect on the temperature. For example, tree species (intensive GR) have demonstrated to mitigate UHIs more efficiently (Herrera-Gomez et al., 2017). Future research could focus on determining which tree species (intensive-type of GR) are better adapted to hot and dry climates to maximize the use of the hectares available for greening in the city of Seville, allowing to achieve a more significant temperature reduction with the number of hectares available.

Urban development often prioritizes vegetation cover over population density (McDonald et al., 2023). Given that Seville is still planning to reach its target population (700,000 inhabitants), urban development can be expected in the upcoming years. For this reason, it is essential to promote an urban environment that works in synergy with green spaces, balancing vegetation with population growth.

6. Conclusions

This research aimed to assess the extent to which green roofs in Seville demonstrate the potential for greening and contribute to a reduced urban heat island effect, determine which district would benefit most from greening and determine the hectares of roofs that would be available for greening. The multi-criteria assessment identified that *Macarena* district should be a prime target for GR implementation due to its high population density, low vegetation cover, and moderate land surface temperatures. The LST and NDVI analysis also corroborated the important role of vegetation to reduce urban temperatures.

The surface analysis of *Macarena* revealed that 55.1 hectares of roofs would be suitable for greening in this district, equal to 74.3% of the total roof surface area. If installed, 28% of the *Macarena* district would be covered in vegetation. This finding already indicates the benefits of green roofs on a district-scale. When looking at the city-wide scale, the extrapolation of the results found a surprising 1081.7 hectares of roofs available for greening. This value exceeds the findings of Herrera-Gomez et al. (2017), which stated that at least 740 hectares of green roofs would be necessary to mitigate the predicted temperature rise (6ºC) in the most adverse climate scenario.

This research found that green cities are possible if people are willing to take advantage of the built-up space. Compulsory policies and incentives from governmental agencies are a rigorous way to initiate their implementation. If Seville were to green all the roofs determined suitable in this study, the city would benefit from a significant reduction in the UHI effect aside from all the smaller scale benefits such as increased air quality, noise insulation, energy efficiency and enhanced biodiversity. The findings of this research indicate green roofs to be a promising path to increase the thermal comfort of Seville, contributing to a sustainable and liveable city.

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Appendices:

Appendix A: LST & NDVI calculation following Avdan & Jovanovska (2016)

Data collection: Data was downloaded from the USGS Earth Explorer, meeting the selection criteria of a cloud cover below 10% and up to date imagery (september 2023).

Selection criteria:

- cloud cover below 10%
- most recent imagery for summer months (September 2023)
- Same/closest month largest difference (ten years was what was publicly available)

Data preprocessing:

Converting numerical values into radiance (TOA). All this information is retrieved from the Band 10 MTL document (.txt) of the landsat 8 data.

1. Top of Atmospheric (TOA) Spectral Radiance ($L\lambda$)

$$L\lambda = ML * Q + AL - Oi$$

Where:

- ML = Radiance Multiplicative Band (No. 10);
- Q = Band 10 image;
- AL = Radiance Add Band (No. 10), and;
- Oi = correction value for band 10

$$L\lambda = 0.00033420 * Band10 + 0.10000 - 0.29$$

2. Conversion of TOA Spectral Radiance to Brightness Temperature (BT) (from Kelvin to Celsius Degrees)

$$BT = (K2/ln(K1/L\lambda) + 1) - 273.15$$

Where:

- K1= K1 Constant Band (No. 10);
- K2 = K2 Constant Band (No. 10), and;
- To convert the result to degrees Celsius (ºC), the absolute zero (approx. -273.15) is added to the BT.

$$BT = (1321.0789/ln(774.8853/L\lambda) + 1) - 273.15$$

3. Normalized difference Vegetation Index (NDVI)

$$\text{NDVI} = \frac{NIR - RED}{NIR + RED}$$

Where:

- NIR = Near-Infrared Band (no. 5)
- RED = Red Band (no. 4)

$$\text{NDVI} = \frac{Band5 - Band4}{Band5 + Band4}$$

Note: A new raster layer was made extracting only NDVI values that are greater than 0.15, due to low (30 meter) resolution of landsat imagery.

A. Using the raster calculator, the NDVI was converted to a binary raster by using the formula NDVI>0.15 =1 and everything below this value would equal 0.
B. NDVI raster layer was converted to a vector layer using the "Polygonize (Raster to Vector)" tool, and masked to the districts of Seville.
C. Once this vector layer was created, to calculate the vegetation index in each district, the "Intersection" tool was used.
    a. District as input layer and NDVI binary vector as overlay layer
D. A new column was created in the NDVI layer for each district to add the area (km^2) that contained NDVI values greater than 0.15.
E. The sum of the area was calculated using **Group Stats**
F. This area was then converted to a percentage of the total area of the district: (NDVI area/total area of district) x 100

4. Land Surface Emissivity (LSE) (average emissivity of an element of the surface of the Earth)

$PV = ((NDVI-NDVI_{min})/(NDVI_{max}-NDVI_{min}))^2$

PV= proportion of vegetation
$NDVI_{max}$= maximum values for NDVI
$NDVI_{min}$= minimum values for NDVI

$$E = 0.004 * PV + 0.986$$

E = Land Surface Emissivity
PV = Proportion of Vegetation
0.986 = correction value of equation

5. Land Surface Temperature (LST)

a. Calculated from BT, NDVI and LSE values

$$LST = BT/(1 + (\lambda * BT/c2) * ln(E))$$

BT = Top of atmosphere brightness temperature (ºC)
λ = wavelength of emitted radiance

- For band 10 = 10.8
- For band 11 = 12.0

E = Land Surface Emissivity
c2 = $h * c/s$ = $1.4388*10^{-2}$ mK = 14388 mK
h = Planck's Constant = $6.626*10^{-34}$ Js
s = Boltzmann constant = $1.38 * 10^{-23}$ JK
c = velocity of light = $2.998*10^{8}$ m/s

Raster Calculator Expression

```
"Brightness_Temp@1" /  ( 1 +  ( 10.8 * "Brightness_Temp@1" / 14388 )  *  ln ( "LSE@1") )
```

<u>Appendix B:</u> <u>LST difference map</u>

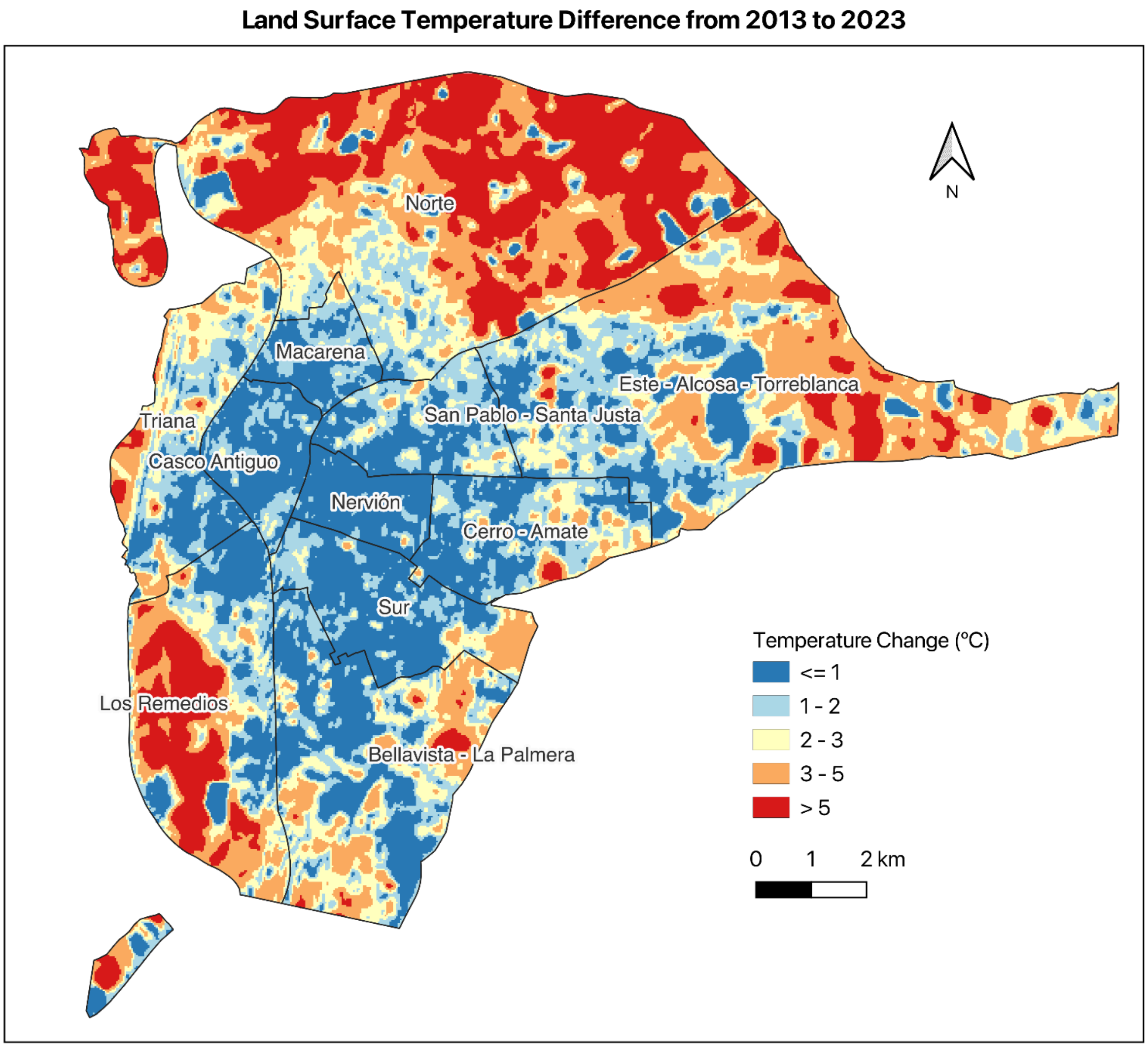


Figure A: Ten year difference map of LSTs in the city of Sevilla (2013 to 2023).

Table 3: Climatic overview of 2013 and 2023. Retrieved from Tutiempo Network (2024a; 2024b)

Climatic factors	**2013**	**2023**
Mean annual temperature (ºC)	18.5	20.3
Mean annual maximum temperature (ºC)	25.3	27.2
Precipitation (mm)	425.67	315.45
Days with precipitation	77	78

Table 4: Mean temperature increase from 2013 to 2023 per district.

District	Mean temperature increase (ºC)
Bellavista- La Palmera	2.34
Casco Antiguo	0.92
Cerro-Amate	2.37
Este	5.00
Los Remedios	4.81
Macarena	1.05
Nervión	0.37
Norte	7.84
San Pablo-Santa Justa	1.42
Sur	1.46
Triana	3.91
Average	2.86

Appendix C: Features selected by random selection

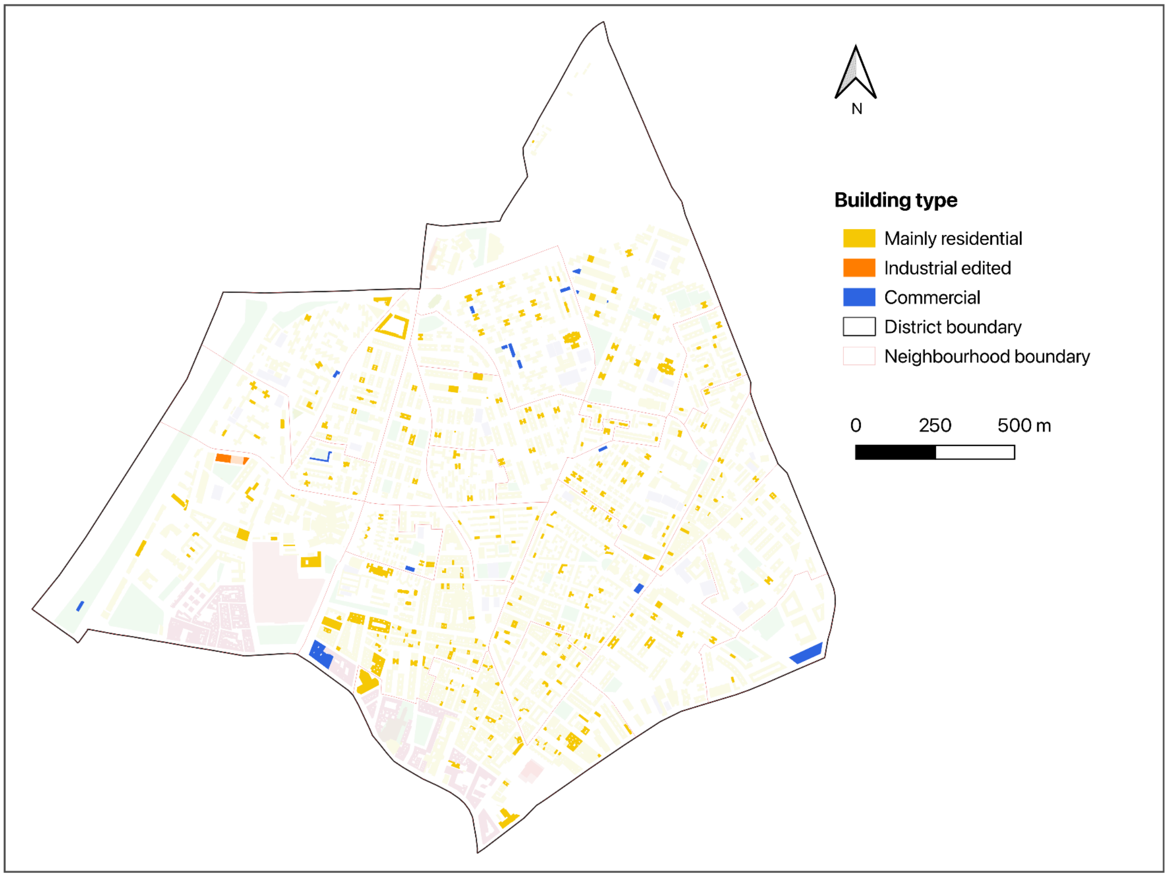
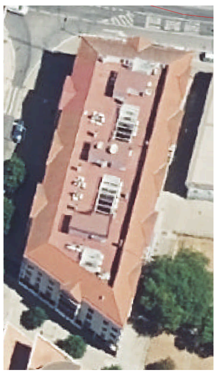
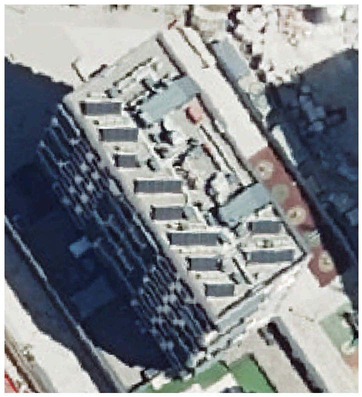
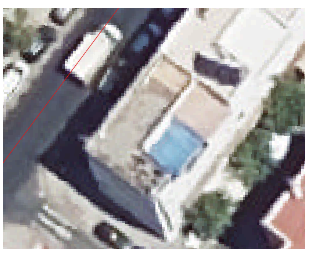
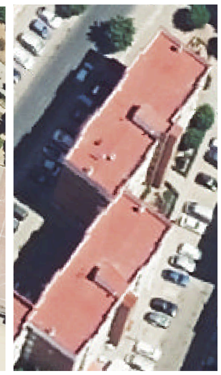


Figure B: A map to show the distribution of the features that were randomly selected using QGIS.

Appendix D: Examples of roofs interpreted as suitable and non-suitable for greening.

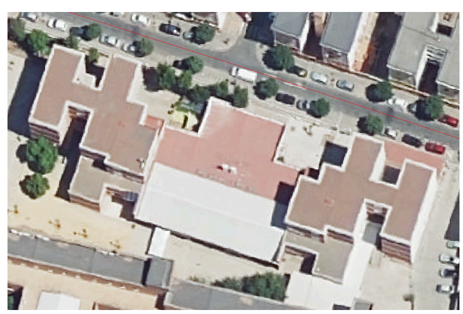
Table A: Screenshots of example roofs selected as suitable and non-suitable based on the suitability criteria.

Unsuitable for green roofs	**Suitable for green roofs**
   	   







Appendix E: City-wide extrapolation of results

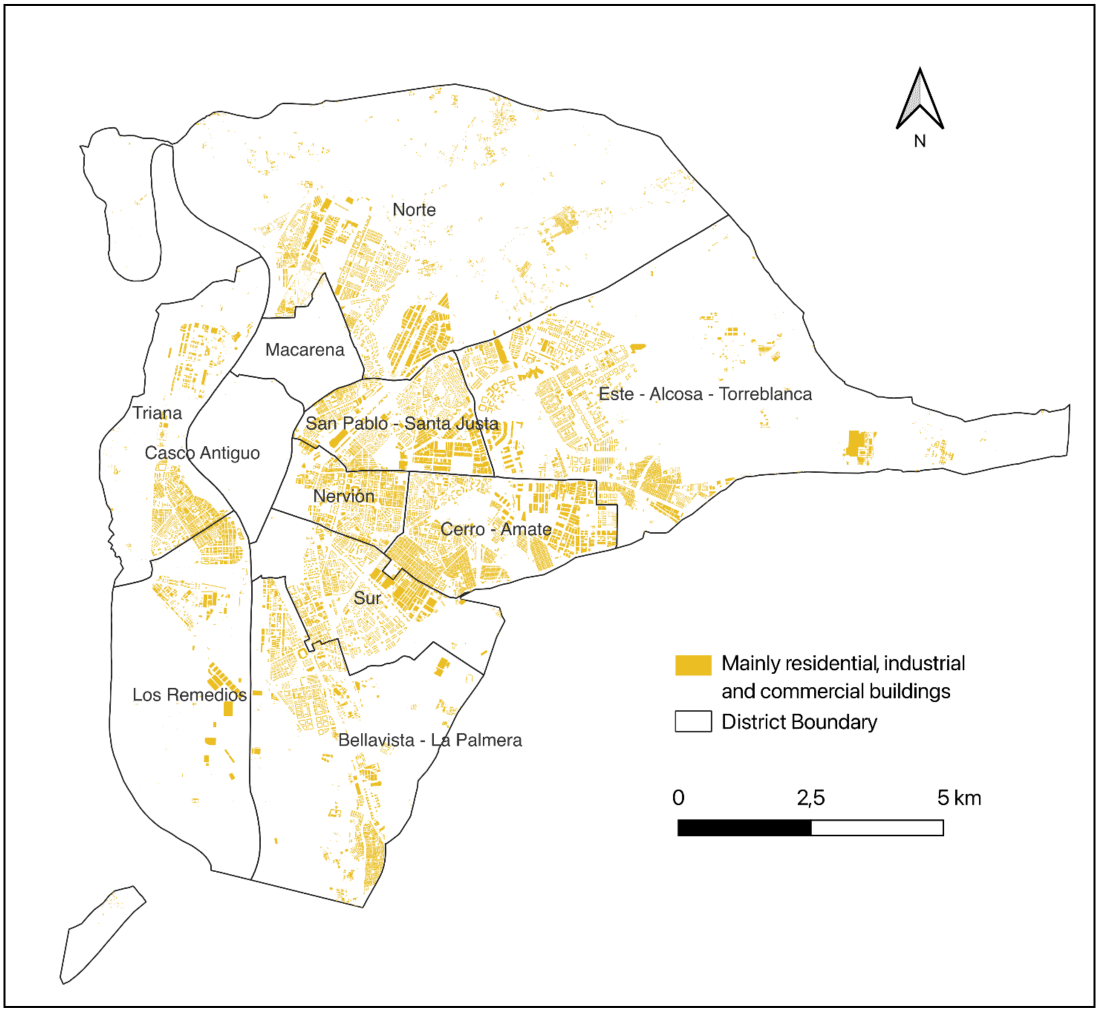


Figure C: Mainly residential, industrial and commercial buildings that were used for extrapolation.

To estimate the hectares available for greening in Seville, SIOSE-AR map was used to determine the surface area of roofs in m^2. Buildings above 40 meters were excluded. Assets of cultural interest were also excluded, including the whole *Casco Antiguo* district which is culturally protected. Sports fields and community use buildings as well. The SA in m^2 available in *Macarena* was added separately to the calculation. The sum of the roofs SA in m^2 was calculated using the open field calculator of the attribute table of this layer.

1. SUM SUPERFICIE_M^2 in Seville (excluding assets of cultural interest, community use, sports field, and above 40 meters) + m^2 suitable for greening in Macarena district = 14,558,675m^2
2. 14,558,675* 0.734 = 10,817,095 m^2 = 1081.7 hectares
3. (1081.7/14209) *100 = 7.61% of the area of Seville.