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Urban Climate Mapping Based on Structural Landscape Features: The Case of Ankara

Nuriye Ebru Yıldız*
Şükran Şahin**

Abstract

The temperature difference between urban environments and urban areas also increases, along with the growing population and building volume in cities. This study aims to map the urban climate of Ankara based on structural landscape features. The method is based on calculating the negative and positive effects of the parameters that shape the urban form on the thermal load and dynamic potential in the city. The urban climate classes are mapped based on the structural landscape character of Ankara city for the purposes of this study. The results of the analysis revealed that the climate class with the highest percentage (Moderate Warming) covers 18.76% of the urban core, while the climate class with the lowest percentage (Very Strong Warming) covers 0.05% of the urban core. When the urban climate classes are evaluated based on districts, it is seen that the heating effect levels of the districts in the urban core are Çankaya (25%), Yenimahalle (18%), Mamak (15%), Etimesgut (14%), Keçiören (11%), Altındağ (8%), and Sincan (8%), respectively. Urban climate maps based on structural landscape character can be utilized in the preparation of spatial plans, particularly in the development of urban open and green space strategies aimed at improving urban climate. It is recommended that this method be applied by the Ministry of Environment, Urbanization, and Climate Change to develop Ankara, with studies conducted in cooperation with local administrations. Additionally, it is suggested that an urban climate branch be established to ensure continuity. Thus, this study can serve as a model for mapping the climate of all cities in the country, informing better planning decisions, and developing sustainable land-use policies.

Keywords: *Ecological indicators, Dynamic effect, Urban heat island effect, Thermal effect.*

*Niğde Ömer Halisdemir University, Faculty of Architecture, Department of Landscape Architecture, Niğde, Turkey (*Corresponding author*)

Email: ebruyildiz@ohu.edu.tr

**Ankara University, Faculty of Agriculture, Department of Landscape Architecture, Ankara, Turkey

Email: sukransahin.tr@gmail.com

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INTRODUCTION

We define urban climate as the local climate that results from the interactions between the regional climate and the settlement at a lower scale. Nowadays, the term "urban climate" also encompasses changes in the natural composition of the atmosphere, including air pollution, temperature, wind, and humidity, due to anthropogenic influences (Ng et al., 2012). Urban temperature, especially surface temperature, is one of the most important primary indicators of urban climate, regulating and controlling ecological processes (Blocken et al., 2007; Li et al., 2005; Pickett et al., 2001). One of the most well-known features of urban climate is the formation of urban heat islands (Koppe et al., 2004). In the early 19th century, the urban heat island effect was first measured and discussed by Lake Howard (Yang et al., 2016). Subsequently, many scientists worldwide have determined that the urban heat island effect is related to land cover and use, vegetation, population density, and weather conditions (Chen et al., 2006). Buildings, roads, and other structural elements can absorb and radiate solar heat more than green spaces and water bodies (Ng et al., 2012). In cities, buildings increase surface and air temperatures due to the solar energy they store, causing microclimatic effects (Elliason, 1990; Oke, 1987). High building volume not only increases the temperature of the area, but also reduces the "Sky View Factor" (SVF). The decrease in SVF is one of the main indicators that the cooling of the urban atmosphere slows down at night (Oke, 1981). Furthermore, long-wavelength radiation is blocked, and energy is released more slowly into the sky in areas with high building density. As a result, cooling tends to occur more slowly in urban centers than in the urban periphery (Ng et al., 2012). This is evident in urban areas, where buildings are densely packed and green spaces are limited, resulting in "islands" of higher temperatures compared to peri-urban areas. These pockets of heat are referred to as "heat islands". On the other hand, heat islands exhibit varying characteristics under different conditions, including day versus night, small versus large cities, suburbs, the Northern versus Southern Hemisphere, and seasonal differences (EPA, 2021). In other words, the concept of an urban heat island refers to the increased temperature in areas of a city with high building density compared to the surrounding rural areas (Koppe et al., 2004). These areas are defined as heat islands with warm cores (Yüksel, 2005). The urban heat island effect is defined as the accumulation of heat that emerges as the most prominent feature of urban climate due to construction and human activities in cities (Oke, 1973; Yang, 2014). The temperature is higher in areas with high building density in the city compared to other areas. On the other hand, there are also cold-core heat islands in green areas and water surfaces within the city, which are cooler than other types of urban areas (Yüksel, 2005).

Urban green spaces reduce the heat island effect in cities through their microclimatic effects, improve air quality and life quality, create habitats for fauna, and contribute to the protection of biodiversity. In addition,

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they provide spaces for both active and passive recreation, making positive contributions to urban aesthetics and image (Yıldız, 2017). Green spaces represent well-vegetated areas, including trees and grass surfaces. Plants cool their surroundings by absorbing the surrounding air (CO2) during both transpiration and photosynthesis. In general, tree canopies are cooler than their surroundings, as trees reflect a significant proportion of solar radiation with their mass. Vegetation absorbs a significant portion of infrared radiation and reflects most of the near-infrared radiation during the photosynthesis process (Dimoudi & Nikolopoulou, 2003). In this context, it is possible to state that vegetation helps reduce the formation of urban heat islands through its cooling effect. Trees can also influence the urban climate by affecting wind speed and direction (Givoni, 1998).

Every 100 m^2 of vegetation added to a park can decrease the air temperature by 1°C (Dimoudi & Nikolopoulou, 2003). Green areas contribute to a decrease of about 0.5°C in air temperature (Shashua-Bar & Hoffman, 2000). According to Gao's (1993) model, when the urban mass ratio is 600% and the road ratio is 20%, a 30% green area reduces the air temperature by approximately 1 °C, while a 50% green area reduces the air temperature by 2 °C. Dimoudi and Nikolopoulou (2003) stated that doubling the size of a park can reduce the air temperature by 1 °C, while tripling the size of a park can reduce the air temperature by 1.5- 3 °C. Therefore, green areas reduce the heat island effect in cities and have a "negative" effect on the thermal load. Therefore, increasing the amount of green space in urban planning and design studies is a crucial strategy for enhancing human comfort, especially in arid and semi-arid climates (Ng et al., 2012).

In general, temperatures in the atmospheric air above the Earth's surface and within the city vary. Therefore, two categories are expressed: surface heat islands and atmospheric heat islands. These heat islands differ in their formation, effects, detection, and measurement techniques, as well as the methods and techniques applied to mitigate their effects and provide some cooling (EPA, 2021). Surface heat islands occur because of higher rates of heat emission and absorption by surfaces such as roads, rooftops, and impermeable ground in cities compared to natural surfaces (Simmons et al., 2008). The impact of surface heat islands reaches its peak during the day when the sun shines. Heat islands that arise due to the presence of hot air in the urban core compared to cooler air in areas outside the urban core are defined as atmospheric heat islands (EPA, 2021). The factors and explanations of the urban heat island effect are presented in Table 1.

In the literature, there are many studies in which urban heat islands are determined at different scales using different parameters, methods, and techniques. Some examples of these studies are given in Table 2.

Table 1. Factors and explanations for the urban heat island effect (EPA, 2021)

Factors	Explanations
Decrease in Natural Landscape Areas in Cities	Green areas provide shade and tend to cool the air by evaporating surface water. However, artificial surfaces in cities such as roofs, sidewalks, roads, buildings, and parking lots provide less shade and moisture compared to natural landscape areas, leading to increased temperatures in the city.
Material Properties of Structures	Artificial materials used in cities, such as roads, sidewalks, or rooftops, tend to reflect more solar energy and absorb and emit less heat from the sun compared to trees and other vegetation and natural surfaces. Often, heat islands occur throughout the day and become more pronounced after sunset due to the slow release of heat from structural materials.
Urban Geometry	The volumes of buildings and the distances between buildings in a city affect wind movement and the ability of building materials to absorb and emit solar heat. Surfaces and structures located in areas with high building density transform into high-temperature thermal volumes that cannot easily release the heat they have absorbed. Cities with narrow streets and tall buildings can form urban canyons, which hinder natural wind flow and prevent the cooling effect that it would otherwise provide.
Heat from Human Activities	Vehicle traffic, heating and cooling systems in buildings, and industrial facilities all emit heat to their surroundings, contributing to the urban heat island effect.
Climate and Geography	Calm and clean air conditions maximize the solar energy reaching urban surfaces and minimize the amount of heat transferred into the atmosphere, leading to more severe heat islands within the city. Conversely, strong wind movements and cloud formations in the atmosphere help reduce the heat island effect. Geographical conditions also influence the urban heat island effect. The topographic structure of the city and its formation can hinder wind movement within the city or contribute to the formation of wind corridors.

Table 2. Studies on the determination of the urban heat island effect

References	Research Details
Duman Yüksel & Yılmaz, (2008)	Between 1985 and 2005, the study investigated surface temperature differences in the metropolitan area of Ankara, focusing on the changes in built-up areas and urban heat islands, using data from fixed meteorological stations.
Chen et al., (2012)	Air temperatures were measured at 80 stations belonging to parks in the city and compared with surface temperatures obtained from Landsat TM thermal bands. The results indicate a temperature difference of approximately 1.74 °C between the green park areas and the surrounding bare areas.
Xiong, et al., (2012)	Between 1990 and 2009, the relationship between NDVI and NDBI indices and heat island distributions were analyzed by regression analyses. The findings indicate that temperature anomalies are particularly high in regions with high construction, population density, and industrial activity.
Tan & Li, (2013)	Multiple regression analyses were performed to examine the relationship between LST values and NDVI in 98 green areas within the city. The findings obtained from the NDVI differences between green areas and areas with high building density show that the cooling effect of green areas varies according to the size and shape of green areas.
Alavipanah et al., (2015)	The effect of surface temperature and land use was determined by comparing MODIS 8-day composite MYD11A2 coded surface temperature images with land use data obtained from the CORINE (2002-2012) database.
Aslan & Koc-San, (2016)	With the help of Landsat 7 ETM+ and Landsat 8 OLI/TIRS data and land cover maps obtained using a random forest classifier, NDVI maps and surface temperature maps obtained from thermal bands, the relationship between land cover and surface temperatures was analyzed.
Canan, (2017)	In four different regions, the maximum urban heat island effect resulting from the geometrical formation of the urban fabric was determined. The findings suggest that the maximum heat island effect may occur at high values in densely urbanized areas with low sky clearances (SVF).
Dihkan et al., (2018)	In a study conducted in the cities of Istanbul, Bursa, Ankara, Izmir, Gaziantep, Erzurum, and Trabzon, the urban heat island effects observed in these cities between 1984 and 2011 were determined and modeled using surface temperature images obtained from the thermal bands of the ASTER satellite.

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When studies on the urban heat island effect are examined, they can be categorized into three main headings based on their method and scale (Duman Yüksel & Yılmaz, 2008). (1) Upper scale (city and its immediate surroundings) and satellite imagery studies. (2) Observation studies covering the city (all or only a part of it) and rural areas, and comparing the data obtained from meteorological stations with the data obtained from the established stations. (3) Lower scale (housing or building island) and numerical modelling studies.

Upon evaluating the information presented in this section, it becomes apparent that numerous parameters contribute to the urban heat island effect, including ecological and land-use-related factors resulting from human impact. These parameters introduce the concepts of 'indicator' and 'ecological indicator', which are used to determine the urban heat island and express the estimation using quantitative methods. Voghera (2011) defines the concept of ecological indicator as 'a set of tools used to measure and evaluate the sustainability and quality of a landscape'. The aim of using these indicators is to characterize the current situation, monitor and/or predict significant changes (Jackson et al., 2000). In short, by using each ecological indicator that affects the urban heat island, quantitative information can be provided about the integrated effect of the elements of the landscape structure on one another. In this way, the integrity of all indicators affecting the urban heat island is ensured, making significant contributions to sustainability.

This study calculated the urban climate of Ankara by considering the negative and positive effects of the parameters that shape the urban form on the thermal load and dynamic potential indicators within the city. Within the scope of the research, six sub-indicators, namely "building volume", "topography", "green areas", "ground coverage", "natural landscape" and "proximity to open space", were evaluated adapted from Ng et al. (2012) and the relatively different climate zones of the city were mapped. The study primarily consists of three stages: (1) exploring national and international literature, (2) determining the urban core boundary in Ankara, and (3) mapping the urban climate. This study is the first national research to map the urban climate in Turkey. Therefore, this study, conducted for the urban core of Ankara, can be regarded as a starting point for other studies in Turkey that map urban climate and develop land-use policies. For this reason, the methods and techniques employed in this study differ from and are unique to other studies in literature. We expect that the study can contribute to the development of practical steps in the process of preparing spatial and strategic plans within the framework of sustainability goals.

MATERIALS AND METHODS

The materials and methods section are described under the headings of study area, data sets, and methodology.

Study Area

The main material of the study is the urban core of Ankara, located between 39°14′46″-40°13′35″ northern latitude and 32°14′24″-33°09′49″ eastern longitude. The city of Ankara consists of central districts including Etimesgut, Altındağ, Çankaya, Keçiören, Pursaklar, Mamak, Gölbaşı, Yenimahalle, and Sincan, while to the east of the city are Elmadağ and Bâlâ, to the west are Haymana, Polatlı, and Ayaş, and to the north are Kazan, Çubuk, and Akyurt districts. The reason for choosing Ankara city as the study area is that the population of the central districts of the city (Etimesgut, Altındağ, Çankaya, Keçiören, Mamak, Gölbaşı, Yenimahalle and Sincan) increased by 52% from 2000 (3.296.337) to 2023 (5.003.857) (TUIK, 2024). Pursaklar district is also one of the 9 central districts of Ankara, but it is not included in the population growth calculation since it gained district status in 2008. In the 23-year period, this population growth in the central districts has also led to an increase in the building density in the city. Therefore, the primary objective of this study is to investigate the impact of urban development in Ankara on the urban climate and to analyze the findings.

In line with the aim and scope of the study, to determine the boundary of the research area, the urbanization levels (urban-rural distinction) of Ankara City were investigated, and a two-stage boundary study was conducted. In the first stage, the 9 central districts of Ankara city determined by the Development Agency were taken into consideration. In the second stage, urbanization levels were analyzed based on land cover for the borders of the 9 central districts, and the obtained urbanization levels were categorized into three classes: "urban core", "urban fringe", and "rural area". Figure 1 shows the geographical location of the study area and the urban core boundary.

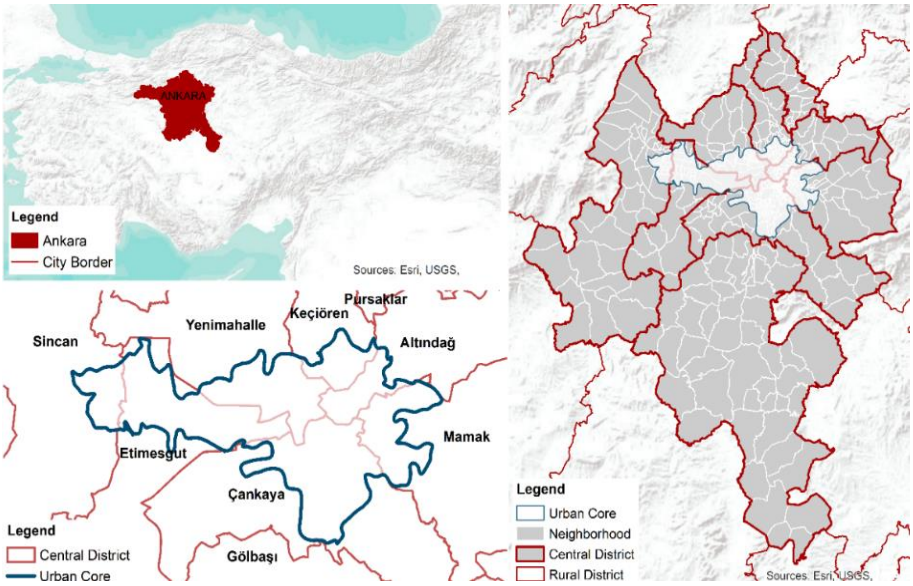

Figure 1. Geographical location map of Ankara

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Data Sets

Table 3 presents the datasets used in this study, their source, and intended use. The projection system of the data sets used in Geographic Information Systems and Remote Sensing analyses is organized as "WGS_1984_UTM_Zone_36N".

Table 3. Data sets and their characteristics

Data Set	Source	Intended Use	Data Type - Type - Resolution - Date
Provincial and district administrative boundaries	HGM (General Directorate of Mapping)	Geographical Location	Data type: Vector Data Type: Polygon
2016 Neighborhood Boundaries	Ankara Metropolitan Municipality Department of Zoning and Urbanization Map Branch Directorate	Geographical Location	Data type: Vector Data Type: Polygon
Building Volume Data	Ministry of Environment, Urbanization and Climate Change, General Directorate of Geographic Information Systems, Department of Geographic Information	Building Volume	Data Type: Raster Resolution 100m x 100m
Digital Elevation Model (DEM)	Copernicus Land Monitoring Service (https://land.copernicus.eu/)	Topographic Elevation Slope	Data Type: Raster Resolution 25m x 25m
2012 Imperviousness Density Data	Copernicus Land Monitoring Service (https://land.copernicus.eu/)	Ground Coverage	Data Type: Raster Resolution 100m x 100m
Geometrically and radiometrically corrected satellite image (2020)	U.S. Geological Survey (USGS)	Green Space Map Natural Landscape Proximity to Open Spaces	Data Type: Raster Satellite: Landsat 8 OLI-TIRS Resolution 30m x 30m Image Date: 29/08/2020

Methodology

The study was conducted in three stages: (1) The study area was identified by the research objectives and scope. A literature review was conducted on theoretical foundations, methods, and research findings, and numerical, verbal, and visual data were collected. (2) To determine the study boundary, the urbanization levels of Ankara City were identified, and the study area boundary was defined using the urban core boundary. (3) Measurement techniques were determined for urban climate mapping, and indicator analysis was completed.

Analyses that will enable urban climate classification within the scope of the methodology are the existing thermal load and dynamic potential of the area. For this purpose, six different sub-indicators are analyzed as structural landscape features: "building volume", "topography", "green areas", "ground coverage", "natural landscape", and "proximity to open space" (Figure 2). The mapping of the city's climate is based on the evaluation of the thermal load, which is determined according to "negative" factors such as building volume that will increase the building volume and "positive" factors such as green areas that will cool the air, together with the dynamic potential (airflow potential) determined according to positive and negative factors. Table 4 presents the negative and positive factors that affect the urban climate.

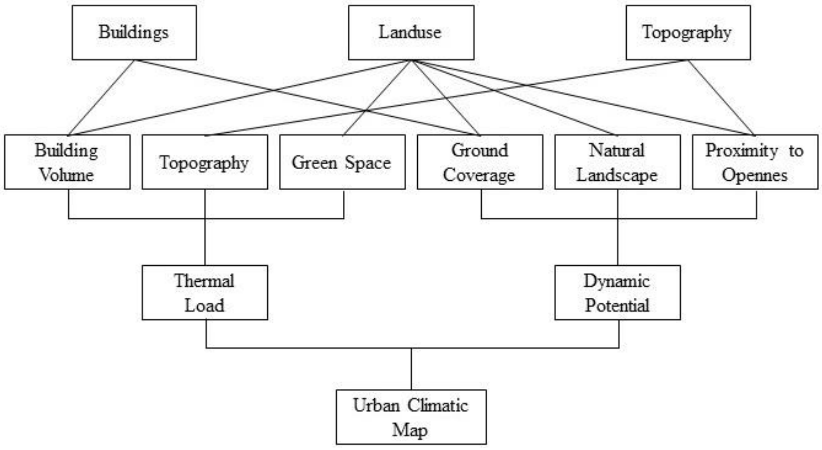

Figure 2. Schematic of the methodology used to determine the urban heat island effect (adapted from Ng et al. (2012))

Table 4. Parameters affecting urban climate (Ng et al., 2012)

Indicators	Effect	Detail	Sub-indicators
Thermal Load	Negative	Building masses	Building Volume
	Positive	Altitude and Elevation	Topographical Height
		Bioclimatic effects	Green Space
Dynamic Potential	Negative	Urban permeability	Ground Coverage
	Positive	Bioclimatic effects / Cold air movement Air mass exchange and Neighbourhood effects	Natural Landscape Proximity to Opennes

RESEARCH FINDINGS

The research findings are presented under three main headings: thermal load, dynamic potential, and mapping of urban climate. Each sub-indicator map for thermal load ((a) Building Volume, (b) Topographical Height, (c) Green Space) and dynamic potential ((a) Ground Coverage, (b) Natural Land, (c) Proximity to Open Space) is shown in Figure 3.

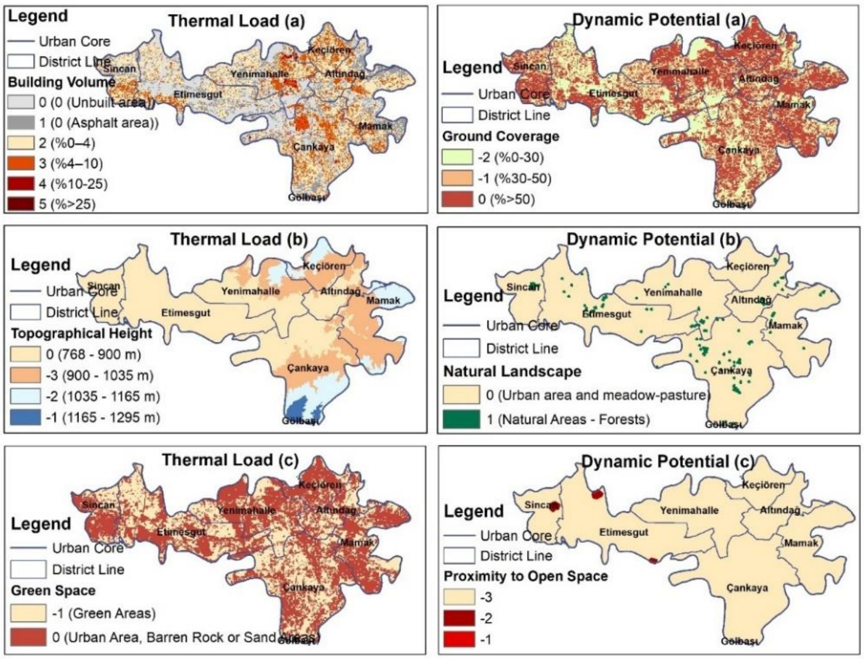

Figure 3. Thermal Load: (a) Building Volume, (b) Topographical Height, (c) Green Space
Dynamic Potential: (a) Ground Coverage, (b) Natural Land, (c) Proximity to Open Space

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Thermal Load

Thermal Load has two important effects on the creation of climate maps. If the area contains high heat stores, such as large stacks of buildings, they have a "negative" effect on the thermal load as they will cause a temperature increase, while differences in height above sea level and green areas have a "positive" effect on the thermal load. The positive and negative effects of building volume, height, and green areas on the thermal load were calculated.

Building Volume: The higher the building volume, the higher the heat capacity and the higher the thermal load. The building density and building volume of the city are key indicators in determining the ventilation conditions and urban temperature. Generally, an urban area with a higher building density will exhibit lower ventilation performance (Givoni, 1998; Hui, 2001; Ng et al., 2012). The building volume data used in this study have a spatial resolution of 100 m x 100 m and contain building volume data (m^3). Building volumes are expressed as a percentage of the highest volume value in the study area and are categorized into six groups in the GIS model. As the building density increases in areas with high building volume, the SVF value decreases, and the associated thermal load increases. In this context, in order to calculate the thermal load due to building density, the building volume data was expressed as a percentage. These values were expressed in six different classes: 0 (areas without buildings), 1 (paved areas), 2 (0-4%), 3 (4-10%), 4 (10-25%), and 5 (greater than 25%) (Table 5).

Table 5. Thermal load values of the building volume (Ng et al., 2012)

Thermal Load	Building volume (Percent)	Classification
Zero	0 (Unbuilt area)	0
Very Low	0 (Asphalt area)	1
Low	% 0 – 4	2
Middle	% 4 – 10	3
High	% 10 – 25	4
Very High	% 25	5

In the building volume map shown in Figure 3, Thermal Load (a), it is possible to say that the building volume has a density of 4% and above in almost all of Çankaya, Keçiören, Altındağ, and Çankaya Districts, south of Etimesgut and Sincan, east of Yenimahalle, and west of Mamak.

Topographical Height: We know that air temperature varies according to altitude. The temperature of a topographically high area is generally cooler than that of a lower area. Topographic height is a crucial indicator in determining the thermal load in cities with rugged topography (Yıldız, 2022). In this study, the EU-DEM v1.1 digital elevation model, with a spatial resolution of 25 m x 25 m, provided by the European Environment Agency (EEA), was used to create the

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topographic elevation map. Since the study area does not differ significantly in terms of topography, this factor was taken into consideration when classifying the digital elevation model, and the values in Table 6 were accordingly reinterpreted.

Table 6. Topographic elevation classes (adapted from Ng et al. (2012))

Topographic Height	Topographic Elevation (m)	Class
Very High	1600-1872	-3
High	1300-1600	-2
Middle	1000-1300	-1
Low	713-1000	0

In the topographic height map shown in Figure 3, Thermal Load (b), it is evident that the highest region of the city core (1295 m) is located in the southern parts of the Çankaya district. East of Mamak, north of Keçiören and Yenimahalle, and south of Çankaya, the topographic height ranges from 1036 m to 1165 m.

Green Space: The most significant success indicator that has a negative effect on the thermal load in cities is the amount of green area (Yıldız, 2022). In this context, the Normalized Vegetation Index (NDVI) obtained from the Landsat 8 OLI/TIRS satellite image was used to calculate the amount of green area. The NDVI equation is given in Equation 1, and the NDVI value resulting from the analysis varies between -1 and 1. The value with the lowest plant density is expressed with "-1", while the value with the highest plant density is expressed with "1". While negative values represent clouds, water, and snow, values close to zero represent rock and bare soil. Very low values of NDVI (-1 and 0.2) correspond to rock, sand, or bare areas; medium values (0.2 to 0.3) represent shrubs and grasslands; and high values (0.3 to 1) indicate trees (ESRI, 2016). Within the scope of the study, for the city of Ankara, areas with a value greater than 0.2 are considered green areas, and areas with a value less than 0.2 are considered as rock and bare soil.

$$NDVI=((NIR-R)/(NIR+R)) \quad (1)$$

To achieve a spatial resolution of 100m x 100m for the obtained data, the cell size of the raster data was first reduced to 1 m x 1 m using the "resample" command in ArcGIS software. Then, the cell size was adjusted to 100 m x 100 m using the "aggregate" command. The raster data, with a spatial resolution of 100 x 100 m, was reclassified into two categories: "-1" and "0", adapted from a study conducted by Ng et al. (2012) for Hong Kong (Table 7).

Table 7. Cell value and classification for green spaces (adapted from Ng et al. (2012))

NDVI Value	Vegetation	Class
-1 – 0.2	Structure, Bare Soil, Rock	0
0.2 – 1	Green Area	-1

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When Figure 3 Thermal Load (c) is analyzed, it becomes clear that the areas outside the structural zones in the city core are designated as green areas. It is possible to say that there are areas with NDVI values between 0.2 and 1 in the east of Etimesgut and Sincan, west of Yenimahalle, inland and north-west of Çankaya, and north-east of Altındağ, which represent green areas. Unfortunately, the findings show that the amount of green areas in Keçiören and Mamak districts is almost negligible.

Calculation of Thermal Load: The values obtained with the "building volume", "topographic height" and "green areas" maps with a spatial resolution of 100 m x 100 m were summed for each pixel with the "raster calculator" command in ArcGIS software and the "Thermal Load" was obtained (Figure 4).

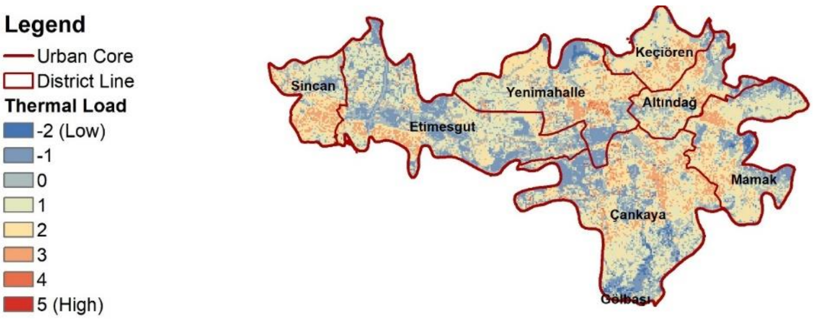

Figure 4. Thermal load map

When 'building volume', 'topographic height', and 'green areas' are evaluated integrally, it becomes apparent that the thermal load generated by the city is high in regions where the building volume is high. The amount of green areas is low. In summary, it can be said that the thermal load is high in the south of Sincan and Etimesgut, as well as in the west, east, and inner parts of Yenimahalle, all regions of Altındağ except the northeast, the west, and south regions of Mamak, and the entire Keçiören district.

Dynamic Potential

Dynamic Potential is also an important performance indicator for climate impacts. Within the scope of this indicator, the ground coverage, natural landscape, and proximity to open spaces of the research area were evaluated. Dynamic potential has two important effects on the creation of climate maps. If the research area contains areas with high ground coverage, it has a negative effect on dynamic potential, whereas if it contains natural landscape areas and is close to open areas, it has a positive effect on dynamic potential (Yıldız, 2022).

Ground Coverage: Ventilation is a key issue in urban planning and building design. Built areas in cities interfere with local-scale wind both horizontally and vertically, negatively affecting air circulation (Perry et al., 2004; Ng et al., 2012). Therefore, a reliable assessment of the aerodynamic characteristics of cities is essential for predicting and guiding urban wind movements (Grimmond & Oke, 1998). There are numerous morphological prediction models developed in the international literature on the subject, which help urban planners determine surface roughness in cities. The ground coverage indicator refers to the ratio of the ground coverage of buildings to their actual physical floors in a region (Ng et al., 2012). The ground coverage ratio is an indicator of the urban permeability, as well as the density of residential areas, and its impact on the urban heat island effect and wind speed. The higher this ratio, the lower the wind speed (Yoshie, 2006).

The "Imperviousness" data produced by the Copernicus Land Monitoring Service was used to determine soil impermeability. Imperviousness data shows the percentage of soil impermeability and its state of change. As is well known, built-up areas result from the replacement of semi-natural land cover or water surfaces with artificial, usually impermeable cover. Imperviousness shows the spatial distribution of artificially covered areas, including the level of soil impermeability per unit area. The degree of impermeability is calculated using a semi-automatic classification based on NDVI and expressed as a percentage (1-100%) (Anonymous, 2020). Within the scope of this study, the imperviousness data should have a spatial resolution of 100 m x 100 m. For this purpose, the cell size of the raster data was first reduced to 1 x 1 m using the "resample" command in ArcGIS software, and then the cell size was reorganized to 100 x 100 m using the "aggregate" command. The ground coverage values of the obtained raster data were classified into three categories as "-2", "-1", and "0" (Table 8).

Table 8. Ground coverage degrees and classes (Ng et al., 2012)

Ground Coverage Status	Ventilation Potential	Ground Coverage Degree (%)	Classification
Low	High	0-30	-2
Middle	Middle	>30-50	-1
High	Low	>50	0

In the ground coverage map shown in Figure 3, Dynamic Potential (a), it is seen that the ground coverage is also high in areas with high building density and impervious surfaces. Unfortunately, it is possible to say that ground coverage is 50% and above in a large part of the urban core.

Natural Landscape: Natural vegetation cover is a crucial indicator of dynamic potential, as it has a cooling effect on the atmosphere and facilitates the movement of cold air. Numerous studies have investigated the impact of surface roughness on wind speed in urban areas. Wind speed is slower in areas with a high degree of roughness and faster in areas with a low degree of roughness. For this reason, it

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can be said that green areas have a lower degree of roughness than residential areas. Therefore, wind speed is higher in green areas than in cities (Oke, 1987). In this study, NDVI data was utilized to determine the natural landscape. In the NDVI data, areas with a value of "<= 0.6" were categorized as "0" and areas with an NDVI value of "> 0.6" were categorized as "1". The obtained data was organized to have a spatial resolution of 100 m x 100 m using the "resample" and "aggregate" commands. Considering the 75% threshold value in the study conducted by Ng et al. (2012) for Hong Kong, the raster data were reclassified into two categories: "0" and "1" (Table 9).

Table 9. Classification used in the identification of natural landscape areas (Ng et al., 2012)

Natural Landscape	**Classification**
Forests	1
Urban area and meadow-pasture	0

Figure 3. Dynamic Potential (b) shows the natural landscape map. Natural areas refer to natural forest lands in the urban core. Unfortunately, there is almost no forest land in the urban core of Ankara.

Proximity to Openness Map: Buildings in cities influence wind speed and direction, thereby negatively impacting natural ventilation within the city. Open spaces in the city, on the other hand, not only contribute to ventilation but also regulate other climatic conditions and reduce the thermal load. When assessing dynamic potential, proximity to the open sea or lakes, as well as slope indicators, should also be taken into consideration. Therefore, within the scope of the research, proximity to open spaces was evaluated with three different indicators: "proximity to water", "proximity to open spaces", and "slope".

Proximity to waterfront map: At this stage, since there is no sea in Ankara City, only lakes were considered. Settlement areas were zoned as 70 m, 140 m, and >140 m according to their distance to the lake shore, and the obtained data was converted into raster data with a resolution of 100 x 100 m. When evaluating the proximity indicator to the water coast, it should be considered in conjunction with the ground coverage indicator, as it affects wind speed and direction. For this purpose, the proximity to water and ground coverage data were overlaid using the "mosaic" command in ArcGIS software and classified into 3 categories as "-2", "-1" and "0".

Proximity to Open Space Map: At this stage, the proximity to open spaces indicator was evaluated by interpreting the building volume and ground coverage indicators together. For this purpose, the ground coverage data was first divided into three classes: "<= 30% (-2)", "30-50% (-1)", and ">50% (0)". Then, the raster data was

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organized with the "resample" and "aggregate" commands with a spatial resolution of 100m x 100m. Since an area with a ground coverage value below 5% is considered an open area, areas with a ground coverage value below 5% are given a value of "-1", and areas with a ground coverage value above 5% are given a value of "0". Similarly, areas with a building density value below 5% were assigned a value of "-1", and areas with a building density value above 5% were assigned a value of "0". The two reclassified raster data were converted into polygons and merged with the "union" command. In the obtained data, areas with a value of "-2" represent "open areas", areas with a value of "-1" represent "areas adjacent to open areas", and areas with a value of "0" represent "non-open areas".

Slope Map: Steep slopes with vegetation cover (>= 40%) have the effect of increasing wind movement and air circulation in the area. In the Hong Kong study, a threshold value of 75% was used to determine the presence of green space (Ng et al., 2012). In this study, for raster data with a spatial resolution of 100x100 m, if the slope is above 40% and the presence of vegetation is 1, these areas have a positive effect on dynamic potential. To determine the slope condition of the study area, a digital elevation model (DEM) was utilized, with a spatial resolution of 100 m x 100 m. Then, using the "reclassify" command, areas with a slope value of less than 40% were reclassified as "0", and areas with a slope value of greater than 40% were reclassified as "1".

Calculation of Proximity to Open Space: "Proximity to water shore", "Proximity to open area", and "slope" maps with a spatial resolution of 100x100 m were calculated with the help of the "mosaic" command in ArcGIS, and the "Proximity to Open Area" map was obtained. Here, in the merging of layers, the layer with the highest value for a cell was taken into consideration, and a new value was assigned; the other two layers were ignored. This means that only the indicator with the maximum value is selected from the three sub-indicators for each pixel to represent the dynamic potential value for the proximity to open space indicator. For example, suppose the proximity to the waterfront indicator has the most significant dynamic potential value for a pixel. In that case, the values of proximity to open space and slope for that pixel are not taken into account.

Figure 3 Dynamic Potential (c) shows the proximity to open space map. The findings show that there is no area with a slope group of 40% and above in the urban core of Ankara. In addition, the natural water surface is unfortunately almost non-existent within the urban core.

Calculation of the Dynamic Potential: The values obtained with the "ground coverage", "natural landscape" and "proximity to open space" maps with a spatial resolution of 100 m x 100 m were summed

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for each pixel with the "raster calculator" command in ArcGIS software and the "Dynamic Potential" map was obtained (Figure 5).

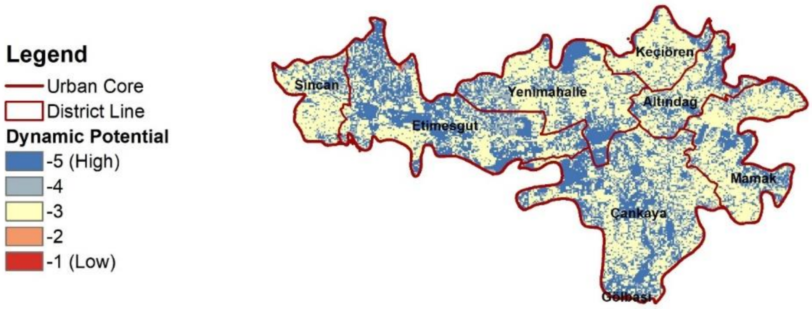

Figure 5. Dynamic potential map

When 'ground coverage', 'natural landscape', and 'proximity to open space' are evaluated in an integrated manner, it would not be wrong to say that ground coverage is the sub-indicator with the highest effect on urban ventilation among the three sub-indicators. Therefore, it is understood that in areas with high ground coverage, the cooling effect of the city is also low. In summary, the ventilation effect of the urban climate is very low in the south of Sincan and Etimesgut, the west, east, and inner parts of Yenimahalle, all regions of Altındağ except the north-east, the west, north, and south regions of Mamak, and the entire Keçiören district.

Urban Climate Map

The heat island effect method applied in the city core is based on a balanced evaluation of the positive and negative impacts on the thermal load and the positive and negative effects on the dynamic potential. At this stage, to map the urban climate, the values obtained from the "thermal load" and "dynamic potential" maps were summed for each pixel using the "raster calculator" command in ArcGIS software, resulting in a new map. Figure 6 shows the urban climate map of Ankara.

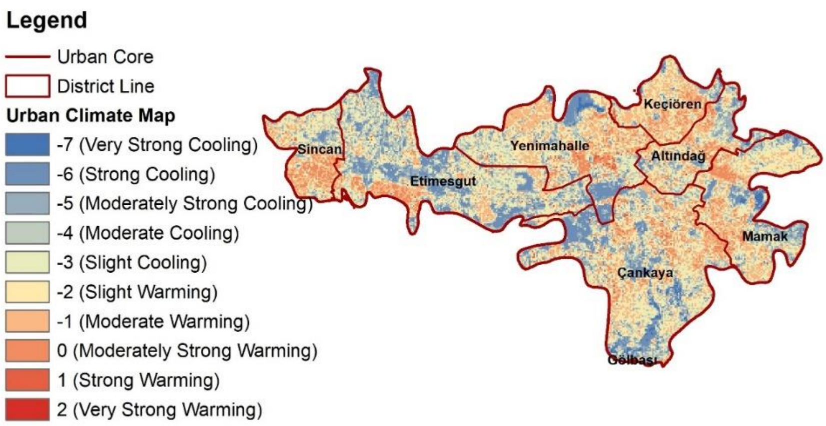

Figure 6. Climate map of Ankara city

Table 10 shows the descriptions and areal magnitudes of the urban climate classes. These climate classes were adapted from Ng et al. (2012) and applied to the urban core of Ankara. The climate classes of Ankara are categorized into 10 classes, ranging from "Very Strong Warming" to "Very Strong Cooling". Very strong warming refers to areas with a very high thermal load and low dynamic potential. In contrast, very strong cooling refers to areas with a very high dynamic potential and a low thermal load. In Table 11, urban climate classes and their areal sizes (ha) based on districts are given in detail.

Table 10. Urban climate classes and their descriptions

Code	Urban Climate Classes	Description	Area (ha)	Perc. (%)
-7	Very Strong Cooling	Very Highly Dynamic Potential and Low Thermal Load	337.8523	1.02
-6	Strong Cooling	High Dynamic Potential and Low Thermal Load	3641.021	11.00
-5	Moderately Strong Cooling	Moderately negative Thermal Load and Good Dynamic Potential	3833.344	11.58
-4	Moderate Cooling	Slightly negative Thermal Load and Good Dynamic Potential	4542.896	13.73
-3	Slight Cooling	Low Thermal Load and Good Dynamic Potential	5913.692	17.87
-2	Slight Warming	Some Thermal Load and Some Dynamic Potential	6034.499	18.23
-1	Moderate Warming	Moderate Thermal Load and Some Dynamic Potential	6210.073	18.76
0	Moderately Strong Warming	Moderately High Thermal Load and Low Dynamic Potential	2436.127	7.36
1	Strong Warming	High Thermal Load and Low Dynamic Potential	130.8792	0.40
2	Very Strong Warming	Very Highly Thermal Load and Low Dynamic Potential	16.32505	0.05

Table 11. Urban climate classes based on districts

District	Urban Climate Classes	Area (ha)	Total Area (ha)
Altındağ	Very Strong Cooling	17	2463
	Strong Cooling	158	
	Moderately Strong Cooling	367	
	Moderate Cooling	344	
	Slight Cooling	428	
	Slight Warming	418	
	Moderate Warming	490	
	Moderately Strong Warming	234	
	Strong Warming	4	
	Very Strong Warming	2	
Çankaya	Very Strong Cooling	149	8741
	Strong Cooling	1035	
	Moderately Strong Cooling	1046	
	Moderate Cooling	1181	
	Slight Cooling	1575	
	Slight Warming	1670	
	Moderate Warming	1466	
	Moderately Strong Warming	563	
	Strong Warming	48	

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District	Urban Climate Classes	Area (ha)	Total Area (ha)
	Very Strong Warming	8	
Etimesgut	Very Strong Cooling	0	7479
	Strong Cooling	1278	
	Moderately Strong Cooling	1191	
	Moderate Cooling	1347	
	Slight Cooling	1537	
	Slight Warming	941	
	Moderate Warming	845	
	Moderately Strong Warming	322	
	Strong Warming	15	
	Very Strong Warming	4	
Sincan	Very Strong Cooling	0	2189
	Strong Cooling	73	
	Moderately Strong Cooling	166	
	Moderate Cooling	292	
	Slight Cooling	407	
	Slight Warming	405	
	Moderate Warming	554	
	Moderately Strong Warming	284	
	Strong Warming	9	
	Very Strong Warming	0	
Keçiören	Very Strong Cooling	23	2199
	Strong Cooling	99	
	Moderately Strong Cooling	144	
	Moderate Cooling	137	
	Slight Cooling	236	
	Slight Warming	564	
	Moderate Warming	753	
	Moderately Strong Warming	231	
	Strong Warming	11	
	Very Strong Warming	0	
Mamak	Very Strong Cooling	87	4351
	Strong Cooling	343	
	Moderately Strong Cooling	438	
	Moderate Cooling	568	
	Slight Cooling	693	
	Slight Warming	991	
	Moderate Warming	879	
	Moderately Strong Warming	351	
	Strong Warming	0	
	Very Strong Warming	0	
Yenimahalle	Very Strong Cooling	54	5499
	Strong Cooling	615	
	Moderately Strong Cooling	444	
	Moderate Cooling	640	
	Slight Cooling	1010	
	Slight Warming	1029	

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District	Urban Climate Classes	Area (ha)	Total Area (ha)
	Moderate Warming	1212	
	Moderately Strong Warming	448	
	Strong Warming	44	
	Very Strong Warming	3	
TOTAL	Very Strong Cooling	338	33097
	Strong Cooling	3641	
	Moderately Strong Cooling	3833	
	Moderate Cooling	4543	
	Slight Cooling	5914	
	Slight Warming	6035	
	Moderate Warming	6210	
	Moderately Strong Warming	2436	
	Strong Warming	131	
	Very Strong Warming	16	

DISCUSSION

The urban climate mapping method is an applicable information and evaluation tool that considers structural landscape features in the preparation of spatial plans and the determination of future projections. Two main components, thermal load and dynamic potential, were used to determine the urban climate. The Urban Climate Map (UC-MAP) encompasses a process in which the relationships and effects of land use, topography, vegetation, and these structural landscape features on thermal comfort are spatially evaluated.

In the national literature, there are remote sensing studies (Alp, 2021; Duman Yüksel & Yılmaz, 2008) and statistical analyses using climate parameters (Çiçek & Doğan, 2005; Bilgili, 2009), which determine surface temperatures for micro-regions in Ankara and inform land use policies. However, these studies do not consider indicators that shape the urban form and climate, such as building density, height, and slope. The resulting urban climate map covers a process in which structural landscape features are evaluated at the boundary of the study area.

Formation of the heat island effect in areas of the city with different landscape characteristics; in other words, different regions of the city in terms of temperature were relatively revealed within the scope of thermal load analyses. The wind generation potential within the city was revealed through the calculation of dynamic potential. Therefore, there is no need to use the wind parameter in determining the city climate classes.

For the calculation of thermal load, "building volume", "topography," and "green areas" indicators were taken into consideration. Within the scope of the research, the urban heat island effect was also found to be high due to the "positive" effect of areas with high building volume, such as the northeast of Çankaya, the southeast of Yenimahalle, and the south of Keçiören, on the thermal load. However, areas with high elevation or green areas, such as the southeast of Çankaya, have a "negative" effect on the thermal load. Therefore, the urban heat island effect is low in these

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areas. In calculating the dynamic potential, three different indicators were used: "ground coverage," "natural landscape," and "proximity to open space." In the city core, especially in Yenimahalle and Keçiören districts, the amount of ground coverage is also high due to the density of buildings. These areas have a "negative" effect on the dynamic potential, and air circulation is very low in these areas. On the contrary, areas with natural landscapes and close proximity to open spaces in and around Eryaman have a "positive" effect on the dynamic potential. Therefore, air circulation is higher in these areas compared to areas with high ground coverage. In this context, it can be said that the urban heat island effect is reduced in areas with high air circulation.

In the study titled "Urban Climatic Map and Standards for Wind Environment" conducted by Ng et al. (2012) and whose method is adapted to this study, it is experimentally stated that the temperature increases in areas where the building volume increases because the "Sky View Factor" decreases, through an algorithm related to the building volume ratio-SVF-temperature value. In this study, the proportional classification of Ng et al. (2012) for building volume, as well as the histogram of Ankara building volume data, were evaluated and interpreted together to classify building volume data in terms of increasing urban temperature. There is a need for research that can be used to classify the building volume by calculating the temperature impact of the building's presence in a given volume. There are studies (Wang et al., 2017; Yao et al., 2020) that divide the city into different structural zones, considering factors such as building density, form, and volume, and interpret the temperature differences in these zones using general statistics and landscape metrics. The fact that different structural regions of the city are either side by side or far apart may alter the impact of building volume or height on temperature. On the other hand, there is a clear need for artificial intelligence and machine learning in the time series analyses of satellite images to be used in surface temperature calculations and time series analyses that will include long-term data.

CONCLUSION & SUGGESTIONS

Table 12 presents the total areas of warming and cooling (in hectares and percentage) by district. When the urban climate classes are evaluated based on districts, it is seen that the heating effect levels of the districts in the urban core are Çankaya (25%), Yenimahalle (18%), Mamak (15%), Etimesgut (14%), Keçiören (11%), Altındağ (8%), and Sincan (8%), respectively. However, when the cooling areas of the districts are analysed, it is understood that Keçiören (4%) has the lowest cooling area among the seven districts.

When the difference between the warming and cooling areas of the districts is evaluated, it is found that the warming area in the Keçiören district is 3226 ha more than the cooling area. Therefore, it can be said that Keçiören has the highest temperature in terms of urban climate among all districts. The reason for this is that although the building volume and the building surfaces that hold the radiation from the atmosphere are high in the Keçiören district, green areas and natural surfaces with a cooling effect are almost non-existent throughout the district.

Table 12. Total warming and cooling areas by districts

District	Warming Area (ha)	Percentage (%)	Cooling Area (ha)	Percentage (%)	Warming & Cooling Area Difference (ha)
Altındağ	1149	8	1315	7	-166
Çankaya	3754	25	4987	28	-1233
Etimesgut	2127	14	5353	30	-3226
Sincan	1251	8	938	5	313
Keçiören	1558	11	640	4	918
Mamak	2221	15	2130	12	91
Yenimahalle	2736	18	2736	15	-27
Total	14796	100	18099	100	-3330

The findings from the study were evaluated, and a proposed map was created to mitigate the heat island effect in the city and enhance the urban climate's cooling effect (Figure 7). In this map, areas with low building density in the city core are suggested as 'afforestation zones', and areas where 'green roof and surface' applications can be made are suggested for regions where building density is high. The amount of green space is limited, and in areas where new green spaces and parks cannot be created, such as Keçiören.

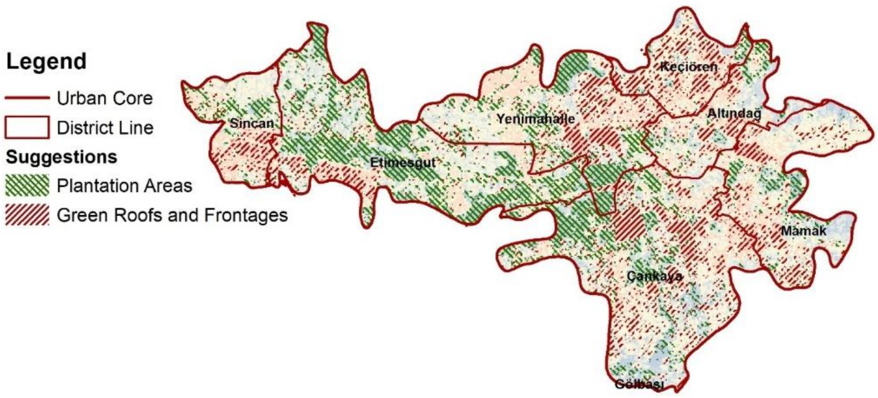

Figure 7. Suggestions to optimize urban climate

Urban climate is a complex issue that is relatively new in Türkiye. Therefore, it has not been fully incorporated into the planning process that determines urban land use policies. Mapping, proper reading, and interpretation of urban climate are crucial, and climate scientists should be consulted when necessary. Although the urban climate map of Ankara is based on a 100 m x 100 m grid, the resulting map should not be interpreted pixel-by-pixel. On the contrary, the pattern, clustering, and extent of pixels provide a better understanding of the general characteristics of a region/district.

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This method can be applied in the calculation of urban climate classes in landscape planning science, where advancements in technology have led to increased scientific knowledge, and in structural landscape characterization studies that build upon this science. At the same time, it sheds light on studies in which climate classes in cities, shaped according to the structural landscape characteristics of other urban landscape areas, such as Ankara's city core, are modeled, and land use policies are developed.

Sustainable development goals, which came into force in 2016 by the United Nations member countries, focus on "ending poverty", "protecting the environment", "taking measures against the climate crisis", "fair sharing of welfare and peace" based on the problems faced by Türkiye and other societies in the world (United Nations, 2024). In line with the objectives of the United Nations, the urban climate mapping method developed in this study will also contribute to the creation of action plans and climate maps at different scales for each city with integrated policies for environmental protection, adaptation to climate change, and increasing resilience against disasters. Improving Ankara's urban climate for the planning of high-quality, comfortable cities is just one aspect of sustainable development in Ankara. In urban planning, other important aspects should be balanced, and synergies should be created as much as possible.

Scientific studies on urban climate are progressing rapidly, particularly in light of the recent 3rd World Climate Conference held in Geneva. The World Meteorological Organization (WMO) emphasizes that, with increasing global warming and climate change, there is a growing need for scientific research on urban climate. Therefore, this study for the urban core of Ankara can be considered a starting point for other studies to be carried out in Türkiye, where urban climate is mapped and land use policies are developed. It is recommended that the urban climate mapping method applied for Ankara should be developed by the Ministry of Environment, Urbanization and Climate Change, that studies should be carried out in cooperation with local administrations and an urban climate branch should be established to provide continuous and up-to-date information for mapping the climate for each city, making better planning decisions and developing sustainable land use policies.

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Resume

Nuriye Ebru YILDIZ graduated from Ankara University, Faculty of Agriculture, Department of Landscape Architecture in 2014. The author completed her Master's degree in 2017 and PhD in 2022 at Ankara University Institute of Natural and Applied Sciences, Department of Landscape Architecture. Between 2016-2023, he took part in the academic staff of the department he graduated from. Since 2023, he has been working in the academic staff of Niğde Ömer Halisdemir University, Faculty of Architecture, Department of Landscape Architecture.

Şükran ŞAHİN graduated from Ankara University, Faculty of Agriculture, Department of Landscape Architecture in 1986. The author completed her Master's degree in 1989 and PhD degree in 1996 at Ankara University, Institute of Natural and Applied Sciences, Department of Landscape Architecture. Since 1987, he has been working in the academic staff of the department he graduated from.

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