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Urban heat island and fringe belt interaction: The role of the urban fringe in heat island mitigation

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Abstract

Fringe Belt (FB) areas are transition zones located between successive areas of urban development. They are typically characterized by open spaces, industrial and institutional areas, and low-density residential areas. An Urban Heat Island (UHI) is a microclimate phenomenon caused by urbanization, characterized by higher surface temperatures in city centers compared to the surrounding area. The primary factors exacerbating the UHI effect are dense development, reduced green spaces and the heat-retaining properties of surface materials. FB areas can mitigate the UHI effect by limiting heat accumulation due to their relatively natural and permeable surfaces. This study aims to analyze temporal changes in FB areas and evaluate their impact on the UHI effect. For this purpose, Landsat satellite images from 1985, 2000 and 2025 were processed using the Google Earth Engine (GEE) platform to obtain land surface temperature (LST) values and map UHI distribution alongside delineation of fringe-belt plots. The results indicate that the UHI effect is relatively low in areas where fringe belts are preserved or minimally developed. Additionally, it was observed that the UHI effect increases as these areas become more developed over time. The study reveals that fringe-belt areas can play an important role in reducing the UHI effect, suggesting that these areas should be integrated into urban planning as cooling buffers. The study emphasizes the necessity of climate-focused approaches in urban planning and suggests evaluating fringe belts as potential microclimatic mitigation areas.

Keywords: fringe belt, urban heat island, remote sensing, land surface temperature, google earth engine

1. Introduction

The Urban Heat Island (UHI) effect is a significant environmental phenomenon characterized by higher temperatures in urban areas than in their surrounding rural areas. This temperature increase is attributed to various factors, including impervious surfaces, energy consumption and anthropogenic heat flux. Understanding the interaction between urbanized areas and their peripheries is crucial for reducing UHI through effective urban planning and landscape strategies that incorporate the urban periphery.

Urban areas tend to have higher surface temperatures due to changes in land cover and settlement density that retain heat. For instance, urbanization significantly contributes to heat retention by reducing vegetation cover and increasing impervious surfaces (Liao et al., 2017; Sobrino et al., 2012). The difference in temperature between urban and rural areas can sometimes exceed several degrees at night when stored heat is released, reaching significant levels (Levermore

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& Cheung, 2012; Dou et al., 2014). As cities expand, the urban fringe — the transition zone between urban and rural areas — plays a crucial role in mitigating these temperature differences. Studies indicate that the careful management of the urban growth — including the expansion of green spaces and water features — can mitigate some UHI effects (Li et al., 2013; Yang et al., 2022; Wang et al., 2019).

1.1. Definition and Importance of Fringe Belt (FB) Areas

Fringe belts (FBs) are transitional zones that emerge between successive settlements during the historical and geographical development of cities, when their growth comes to a halt (Conzen, 1960; Whitehand, 2001). The structural and functional heterogeneity of FBs is contributed to by the diverse land uses that contain open spaces, industrial and institutional areas, as well as low-density residential areas. This diversity characterizes FBs as morphological and historical traces in the interpretation of urban form (Conzen et al., 2012).

FB plots are sparser than residential areas due to their larger sizes and provide important clues for understanding continuity and discontinuity in urban form. They are not merely physical buffers, but also morphological thresholds conducive to explain the direction, timing and strategy of urban growth (Whitehand & Morton, 2006; Ünlü, 2013). Sometimes indicating a pause or change in direction in a city's expansion, FBs also bear traces of planning policies, property structures and socio-spatial dynamics (Barke, 1974).

However, the importance of fringe belt areas is not limited to providing historical insights. These areas can also play a critical role in enhancing urban ecological resilience. In particular, their contribution to urban air circulation, high permeable surface ratios and favorable locations for green space continuity make these areas effective at balancing the urban microclimate. Using the example of Birmingham, Hopkins (2011) stated that fringe belts are stable and continuous natural areas that contribute to urban ecosystem integrity, emphasizing that these areas should be prioritized for protecting urban air movement and ecosystem services.

With their ability to follow the natural topography, high permeable surface ratio, distance from artificial heat sources and wide-open spaces, FBs can provide microclimatic areas that enable air circulation within the city, support biological diversity and balance the heat island effect (Hopkins, 2011; Görgülü & Görgülü, 2021). Therefore, fringe-belt areas should be considered in contemporary planning approaches as components of the future climate-sensitive urban form, not merely as remnants of the past. Similarly, Kirby et al. (2024) demonstrated that unbroken green belts influence temperature distribution at the urban scale and alleviate thermal loads on settled areas.

In the Turkish context, Hazar and Özkan (2020) argues that fringe belts offer significant potential for restructuring urban landscapes through nature-based solutions. This is particularly due to their capacity to create permeability, continuity and climatic buffer zones. These areas should therefore be integrated into spatial planning tools. Görgülü and Görgülü (2021) define fringe belts as critical threshold areas that enable permeability between the built environment and natural systems, providing microclimatic balancing and ecosystem services. In this context, fringe belts are indispensable components of climate-resilient urban planning.

1.2. Theoretical Foundations of the Interaction Between UHI and FB

The interaction between the UHI effect and green infrastructure areas is addressed within a spatial theoretical framework based on urban form and land use diversity. The UHI effect is a well-documented climatic phenomenon characterized by higher temperatures in urban areas compared to rural surroundings. It results from heat emitted by human activities, reduced vegetation cover and the density of impervious surfaces (Oke, 1982; Voogt & Oke, 2003). The intensity of this effect is influenced by various factors, including surface temperature, the heat storage capacity of building materials, and the spatial arrangement of building density.

In contrast, fringe-belt (FB) areas are defined as transition zones that have developed at different stages of urban growth. They are characterized by fragmented land use patterns, low building densities, and relatively high proportions of open and green spaces (Conzen, 1960; Whitehand, 2001). Thanks to these structural characteristics, FBs provide microclimatic advantages such as higher evaporation potential, lower heat absorption, and better air circulation. This makes them a significant contributor to thermal comfort compared to densely built-up urban centers.

In theory, FBs function as morphological and ecological buffer zones and have the potential to mitigate the urban heat island (UHI) effect. These areas are an important component of the historically layered urban form and have played a balancing role against urban pressures over time. Furthermore, urban metabolism and thermal zoning approaches show that the distribution of vegetation and open spaces can significantly impact urban thermal regimes (Grimmond, 2007; Emmanuel & Krüger, 2012).

In this context, integrating FBs into climate-sensitive urban planning can help preserve historically shaped urban structures while reducing heat-related environmental stress. The theoretical basis of this interaction emphasizes the strategic importance of canopy belt zones for long-term climate adaptation and urban thermal comfort.

1.3. Literature Gap and the Aim of This Study

Studies of FB areas have largely focused on their morphological evolution and historical development processes within urban growth models (Conzen, 1960; Whitehand, 2001). However, the environmental regulatory capacities of FB areas, particularly with regard to their potential role in mitigating the UHI effect, have not been sufficiently addressed in the literature. Studies on the UHI effect have generally focused on city centers and densely built-up areas, largely neglecting the potential contributions of fringe-belt areas.

This study aims to reveal how fringe-belt areas can reduce the UHI effect by considering their morphological, socio-economic, and environmental functions. To this end, the relationship between the spatial structure of fringe-belt areas and their thermal behavior is analyzed using satellite images and surface temperature data from different periods. The study intends to provide a new perspective on UHI literature and contribute data-driven insights to urban planning and climate adaptation strategies.

2. Methods and Materials

2.1. Study Area

This study examines Adana, one of Turkey’s largest metropolitan centers. Situated in the south-eastern region of the country, it lies within the fertile Çukurova (Cilician) Plain. Characterized by rapid urbanization, diverse land use patterns and a significant historical and geographical context, Adana is an ideal case study for analyzing fringe-belt areas.

Throughout the 20th and 21st centuries, Adana has experienced significant urban sprawl, particularly to the north, east, and west. This provides a dynamic context for examining the spatial, ecological, and socio-economic characteristics of FB. Various factors have influenced urban development, including its strategic location, regional migration movements, and infrastructure investments. However, Adana's climatic characteristics also significantly influence its urban and ecological structure. According to the Köppen climate classification, the city exhibits the characteristics of a hot Mediterranean climate, with hot and dry summers and mild and rainy winters. During the summer months, especially July and August, temperatures frequently exceed 35°C, while in winter, temperatures rarely drop below 5°C. The annual average rainfall is approximately 650–700 mm, with most precipitation occurring between November and March. These climatic conditions support vegetation in the surrounding areas and directly influence land use preferences in the surrounding areas, particularly with regard to green spaces.

In other words, due to its rapid urbanization, climatic characteristics and morphological structure, Adana is a relevant example for studying fringe-belt dynamics, enabling research into the relationships between urban growth, ecological resilience and socio-spatial transformation (Figure 1).

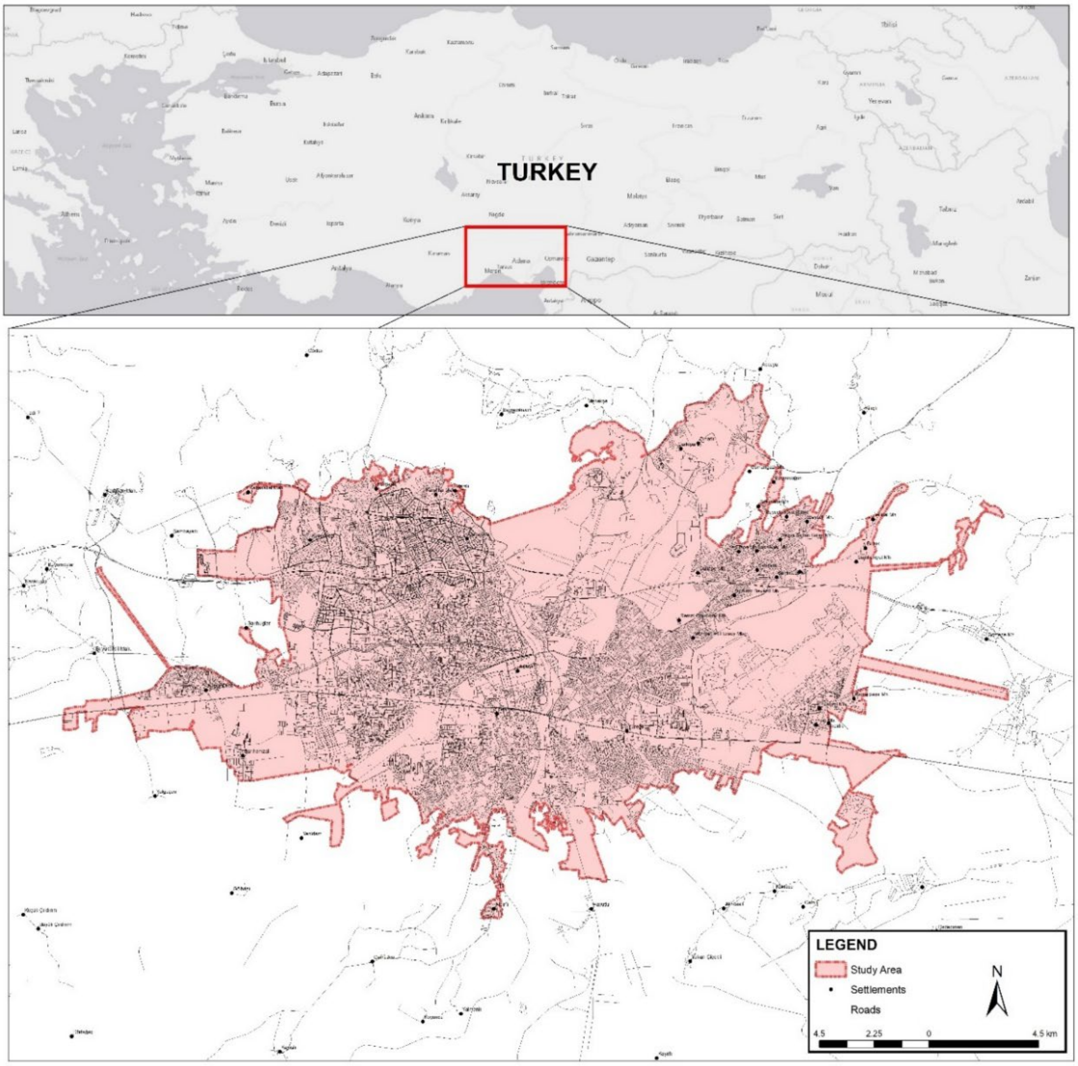

Figure 1 Location of study area

In the first step of the study, the fringe belts were digitized and Landsat 5 TM, Landsat 7 ETM+ and Landsat 8 OLI/TIRS satellite images from 1985, 2000 and 2025 were used to calculate the normalized UHI index. The images were obtained through the Google Earth Engine platform. The UHI value obtained for each fringe-belt plot was then manually assigned to that plot for each analyzed year, in order to investigate the temporal variation of the UHI effect within different land types (Figure 2).

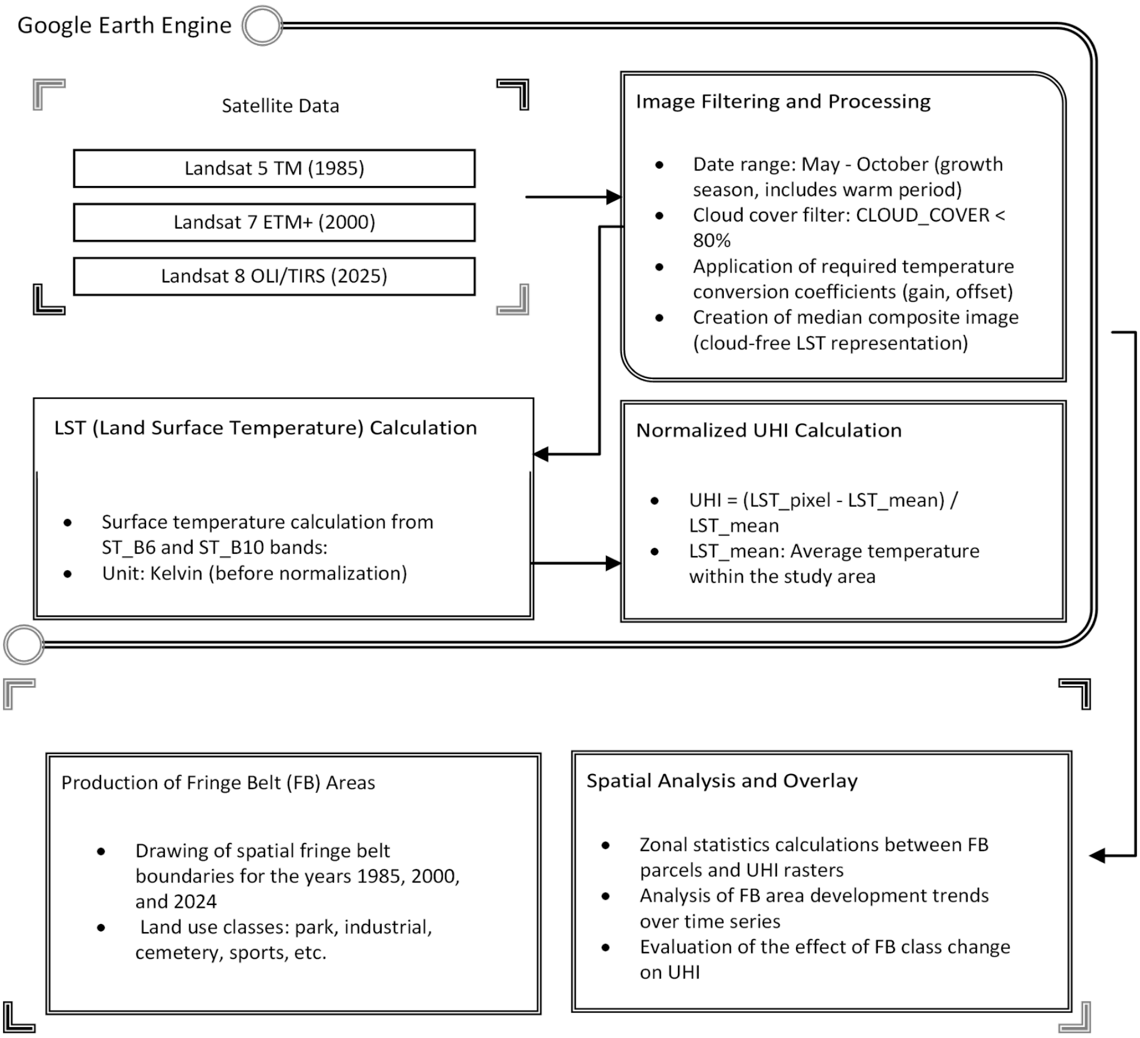

Figure 2 General framework of the study

2.2. Analysis of Fringe Belts

The fringe-belt analysis comprises three main stages. The first stage involves delineating the fringe-belt plots. The next stage is identifying their land uses and determining the changes they have undergone. As this research relates to the UHI effect, the focus is primarily on the first two stages.

Fringe-belt plot delineation is conducted for the years 1985, 2000 and 2025 within the scope of time series analysis. To this end, information was collected from old maps and records, aerial images, and field observations. Alongside today's digital maps, historical maps such as land registry maps, city plans and land use maps from 1985 and 2000 were utilized. However, one of the biggest challenges was the lack of necessary data for creating fringe-belt plots in these historical maps. This issue was resolved by redrawing the land boundaries of the relevant periods using existing digital maps. Additionally, high-resolution aerial photographs from 1985 and 2000, as well as current photographs, were used to clarify the land boundaries. Analogue maps from 1985 were digitized and georeferenced. Data from 2000 and 2025 were evaluated using satellite imagery and urban datasets.

Periodic urban growth data obtained from time series analysis was overlaid with fringe-belt land uses, enabling comparative evaluations of changes in these areas. Accordingly, fringe-belt plots were categorized into four main land-use classes: industrial areas, institutional areas, open areas and other uses (storage, temporary settlements, mixed uses, etc.). These categories enabled the effects of changing urban form on the fringe belt to be interpreted in more detail over different periods (Table 1).

Table 1 Fringe-Belt Classification

Industrial Areas	**Institutional Areas**	**Open Green Areas**	**Other Areas**
Industry	Administration	Public Park	Sports Areas
Warehouse-service	Government	Cemetery	Undefined Area
Medium-sized industry	School		Abandoned Area
Manufacturing	University		Commercial Area (shopping mall, business center)
Transport	Hospital		
	Community Center		
	Military Zone		
	Religious		

Following this arduous and protracted process, the fringe-belt areas of Adana for the years 1985, 2000 and 2025 were delineated. Subsequently, the inner, middle, and outer environmental belts within the built-up area were mapped for these periods using ArcGIS software.

2.3. Urban Heat Island (UHI) Mapping

The study also examined the fringe-belt patterns formed in 1985, 2000, and 2025 by conducting UHI analyses simultaneously. In this process, satellite images, orthophotos, existing maps, and urban plans were interpreted collectively; raster-format data were digitized in GIS-based environments and integrated into the analysis process. Consequently, both the spatial spread of urbanization and the formal and functional characteristics of fringe-belt areas were clearly demonstrated.

The present study utilized satellite imagery from various years to analyze the long-term alterations in the UHI effect, employing land surface temperature (LST) data as the primary investigative metric. In this context, satellite data from Landsat missions in 1985, 2000, and 2025 were utilized to examine the temporal development of the UHI effect in Adana province. The Landsat satellite is part of the Earth Observation Program, the world's longest-running and most comprehensive satellite-based Earth observation program, conducted by the U.S. Geological Survey (USGS) and NASA. Initiated in 1972, this program furnishes a significant data source for the monitoring of alterations in land cover and land use over time. Landsat images are utilized in a variety of disciplines, including urban studies, environmental monitoring, agriculture, forest management, water resources, and climate change, due to their medium spatial resolution of 30 meters (NASA, 2022; USGS, 2023).

The relevant images were obtained through the Google Earth Engine (GEE) platform, which has cloud-based computing and large-scale data processing capabilities. In selecting the images, priority was given to scenes exhibiting high representativeness of the study area, favorable atmospheric conditions, and low cloud cover. The 1985 image was obtained from the Landsat 5 Thematic Mapper (TM) sensor, as demonstrated in Figure 1. This date is significant as it marks the initial stage of Adana's post-industrial urban expansion. The second image, acquired in 2000, was also obtained from Landsat 7 ETM+ and reflects the transformations in land use that occurred during the intermediate stage of urban development. The most recent image was acquired from the Landsat 8 Operational Land Imager/Thermal Infrared Sensor (OLI/TIRS) satellite in 2025, enabling analysis of heat distribution (Table 2).

Table 2 Satellite Sensors, Acquisition Dates, and Spatial Resolutions Used for UHI Analysis

Satellite Name	**Date**	**Resolution**
Landsat 5 TM	1985	30 meters
Landsat 7 ETM+	2000	30 meters
Landsat 8 OLI/TIRS	2025	30 meters

Land surface temperature (LST) calculations were performed with consideration for the technical characteristics of each satellite platform. Initially, top-of-atmosphere (TOA) radiance values were calculated from the thermal bands; subsequently, the brightness temperature was obtained using these values.

All processing steps were executed within the GEE environment, utilizing the JavaScript programming language to ensure that data from different years was processed using a consistent method. The LST layers obtained were analyzed comparatively in both temporal and spatial contexts in order to assess changes in heat distribution in urban areas. The LST formula calculated from the thermal bands of the Landsat 5 satellite was utilized for Landsat 5, while the surface temperature for Landsat 8 was obtained directly from the "ST_B10" band provided in GEE. The difference between the LST value of each pixel in the study area and the average LST value of the surrounding reference non-FB areas was calculated by converting the values from Kelvin to °C. Consequently, the temperature values were subjected to standardization, thereby facilitating the creation of UHI maps. In order to evaluate the UHI effect in fringe belt plots, normalization was performed by comparing the average of the non-fringe-belt regions within the study area. This approach yielded anomalies in the fringe-belt plots. The UHI effect was calculated using the following equation:

$$UHI = \frac{T_{pixel} - T_{mean\_non-FB}}{T_{mean\_non-FB}} \quad (1)$$

Where T_{pixel} is the temperature of the plot in the fringe-belt and T_{mean_non-FB} is the average temperature outside these areas. The normalized UHI maps were divided into five classes according to the lowest and highest pixel values in the region (Table 3).

Table 3 Classification Scheme for Normalized UHI Effect Used in This Study

Classes	UHI Range	Label
1	< - 0.030	Very Cooling Effect
2	-0.030 – 0.000	Cooling effect
3	0	Neutral Zone
4	0.010 – 0.020	Warming Effect
5	> 0.020	Very warming effect

3. Results and Findings

3.1. Urban Growth and Fringe-Belt Formation

In the early 20th century, Adana was a small city located in the fertile agricultural region of Çukurova, where irrigation-based agricultural production was prevalent. The initial significant development took place in the late 19th century, coinciding with the emergence of commercial activity centered on cotton farming and the augmentation of railway connections (Sönmez, 2011). Subsequently, the urban area expanded in a northerly direction, traversing the initial fringe belt – the inner fringe belt – to reach its current extent. The initial urban development plan, formulated by Hermann Jansen and promulgated in 1940, designated this particular area of the city as the primary development zone.

Following the 1950s, urban expansion was propelled by the development of irrigation technologies and the substantial increase in agricultural productivity. The establishment of the Mersin Port and the subsequent intensification of trade relations with Mersin further contributed to Adana's rapid development. The 1967 urban development plan sought to address this rapid growth by proposing new residential areas, with planning focused on expanding toward the northern and northwestern peripheral areas (Altunkasa, 2004). Between the years 1940 and 1967, the city of Adana underwent significant urban development, particularly in terms of its peripheral infrastructure. During this period, the city established its second fringe belt, which was developed in close proximity to the railway line. In the absence of alternative explanations, it can be posited that the industrial uses present in the western region, in conjunction with the airport area, have contributed to the formation of the second fringe belt, which is otherwise referred to as the middle fringe belt.

By 1985, the formation of a middle fringe belt persisted, and a third belt – the outer fringe belt – became apparent in the built-up area. Notwithstanding the occurrence of urban expansion, particularly in the northern and western directions, new development areas have not been fully incorporated into the built-up area. During this period, there was an increase in the number of larger fringe-belt plots, particularly in industrial areas, military areas, the airport, and university areas. Despite the larger plots being located in the outer fringe belt, institutional uses, including education, healthcare, and administrative functions, predominated in the former fringe belts (Figure 3).

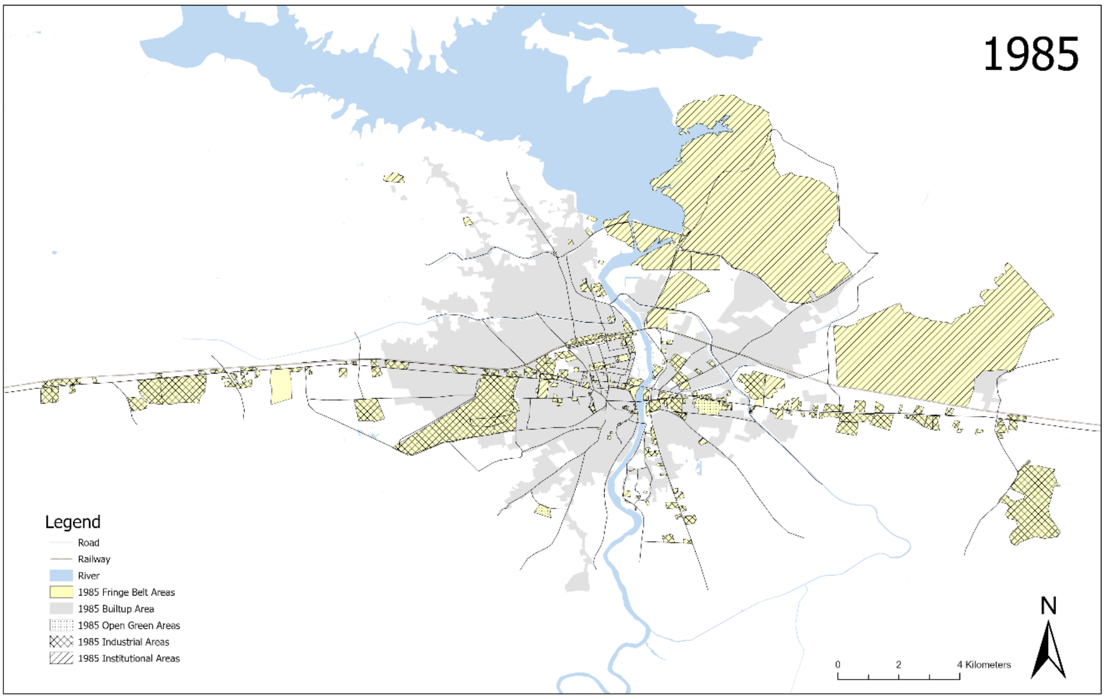

Figure 3 Fringe belts of Adana and the built-up area in 1985

In the late 1990s and early 2000s, an increase in urban density and a trend towards a multi-centered structure were observed in Adana. In the 1990s, a series of revisions to urban development plans resulted in a comprehensive restructuring of the urban structure of Adana. This restructuring was underpinned by a strategic framework comprising five distinct development sectors: northeast, northwest, southeast, southwest, and central (Altunkasa, 2004). During this process, the city incorporated peripheral settlements such as İncirlik, Balcalı, Yeşilbağlar, and Buruk and faced intense development pressure, particularly on the areas around the Seyhan Dam Lake in the north (Zorlu & Sögüt, 2019). While the inner and middle fringe belts were consolidated, the outer fringe belt continued to form, especially through large-scale public investments (Figure 4).

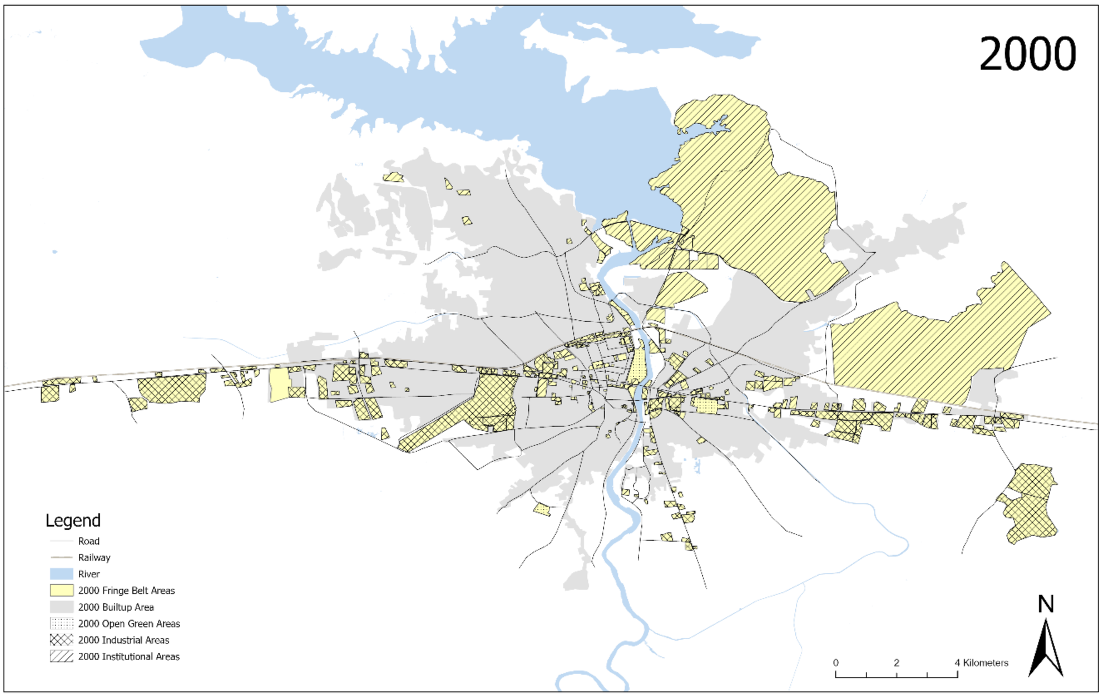

Figure 4 Fringe belts of Adana and built-up area in 2000

By 2025, significant changes in the inner and outer fringe belts were observed. Firstly, there was fringe-belt alienation, which refers to a change in FB use to non-FB use. Secondly, there was a change in land use from one FB use to another. The former is evident in the middle fringe belt, where a process of industrial transition has occurred, with older factories being converted into shopping centers. In contrast, the latter is observed in both the inner and middle fringe belts, as evidenced by the transformation of some industrial plots into institutional use. Conversely, the outer fringe belts are still undergoing a development phase, with the emergence of new institutional structures (Figure 5). The natural threshold areas in the north and west have been subject to high-density development over time, which has also exerted development pressures on the fringe belt areas. This situation has had a detrimental effect on the climatic and ecological characteristics of settlements, thereby increasing the UHI effect.

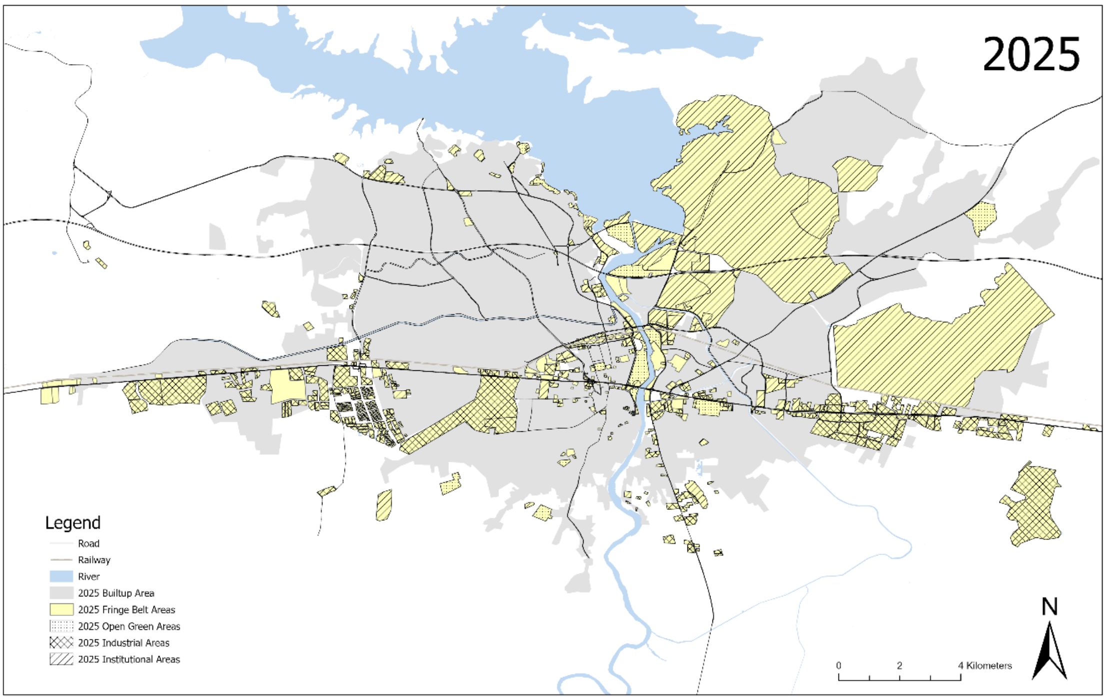

Figure 5 Fringe belts of Adana and built-up area in 2025

The sparse structure of fringe belt areas underwent a gradual densification between 1985 and 2025. This transformation was characterized by the aggregation of building complexes, the augmentation of building footprints, and the reduction of open spaces. Consequently, fringe belt areas underwent a degradation not only in their spatial characteristics but also in their functional and environmental attributes.

3.2. Changes in the Size and Characteristics of the Fringe Belt Between 1985–2000–2025

Between 1985 and 2025, the city of Adana underwent substantial urban expansion. While urban development was primarily focused on the city centre and its surroundings until 1985, the city began to extend to the north and west in the 2000s; the 2025 built-up area exhibits a more intense, dispersed, and fragmented structure in these directions. This phenomenon has precipitated not only an alteration in the boundaries of built-up areas but also a substantial modification in the spatial relationship between the fringe belts and the city (Figure 6).

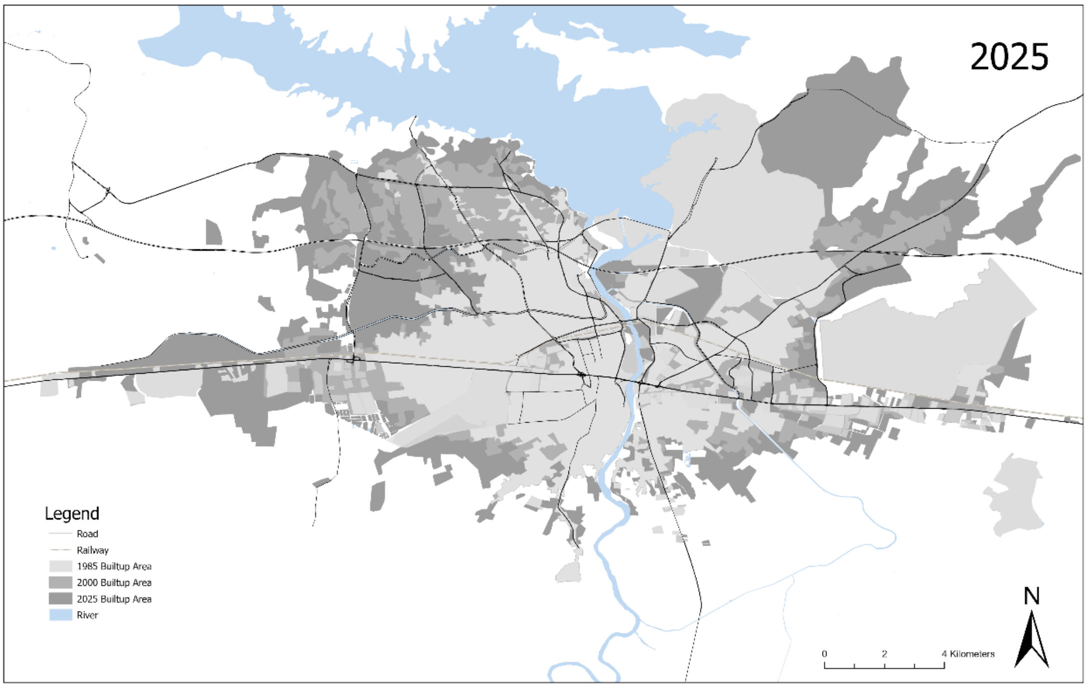

Figure 6 Changes in built-up area by the years

Spatial analyses and quantitative comparisons have been used to reveal changes in the size and functional distribution of fringe-belt areas. As demonstrated in Figure 1, the area of the fringe-belt area increased from 54.3 million m² in 1985 to 55.9 million m² in 2000, and further to 83.3 million m² in 2025. However, it should be noted that this change is not only quantitative but also qualitative (Table 4 and Figure 7).

In 1985, the predominant land use in fringe belts was institutional areas (e.g. universities, hospitals, administrative units) at 71%, while industrial areas ranked second and formed a functional buffer, delineating the urban centre and the environmental threshold. During this period, open green spaces occupied a very limited area and were scattered within the fringe belt (Table 4).

Table 4 Land Use Distribution Over the Years (1985, 2000, 2025)

Year	Land Use	Area (m²)
1985	Industrial Areas	14.216.190,84
	Institutional Areas	38.629.686,56
	Open Green Areas	1.151.142,12
	Other	305.254,76
	Total	54.302.274,28
2000	Industrial Areas	14.882.844,00
	Institutional Areas	39.122.200,48
	Open Green Areas	1.683.973,00
	Other	204.733,67
	Total	55.893.751,15
2025	Industrial Areas	32.363.140,00
	Institutional Areas	44.207.321,00
	Open Green Areas	5.183.881,00
	Other	1.608.919,00
	Total	83.363.261,00

By the year 2000, while the dominance of institutional areas persisted, an increase in the absolute size of industrial areas was observed. However, a decline was observed in the "others" category (storage, temporary settlements, undefined areas, etc.), although not a dramatic change.

The 2025 fringe belts mark a pivotal moment in which both spatial and functional intensification become evident. In particular, there has been a marked increase in development pressure in the older fringe-belt areas, which are located within the inner city. A significant proportion of these areas have undergone a transformation, resulting in the loss of their original functional character and subsequent transformation into service areas for commercial, service and administrative functions. It is indeed noteworthy that high-density developments, including shopping centers, multi-store business centers, and private healthcare facilities, have become pervasive in these areas. This phenomenon underscores the turning of fringe-belt areas from mere transition zones to focal points of urban transformation, leading to increased plot density.

It is evident that industrial areas have attained approximately 32.4 million m², constituting the predominant share within the fringe belts. Institutional areas have undergone continuous expansion, with open green spaces reaching a substantial magnitude, amounting to 5.1 million m². This increase is primarily attributed to the development of previously vacant areas located outside established urban areas. The percentage distributions presented in Figure 7 provide a clearer visualization of this structural change. In 1985, approximately 71% of the fringe belt consisted of institutional uses, while this ratio decreased to 53% in 2025; during the same period, the ratio of industrial areas increased from 26% to 39%. Warehouses and associated service activities were predominant within industrial areas, superseding the presence of factories. Conversely, the proportion of open areas exhibited a marked yet modest rise, from 1.5% to 6.2% of the total area.

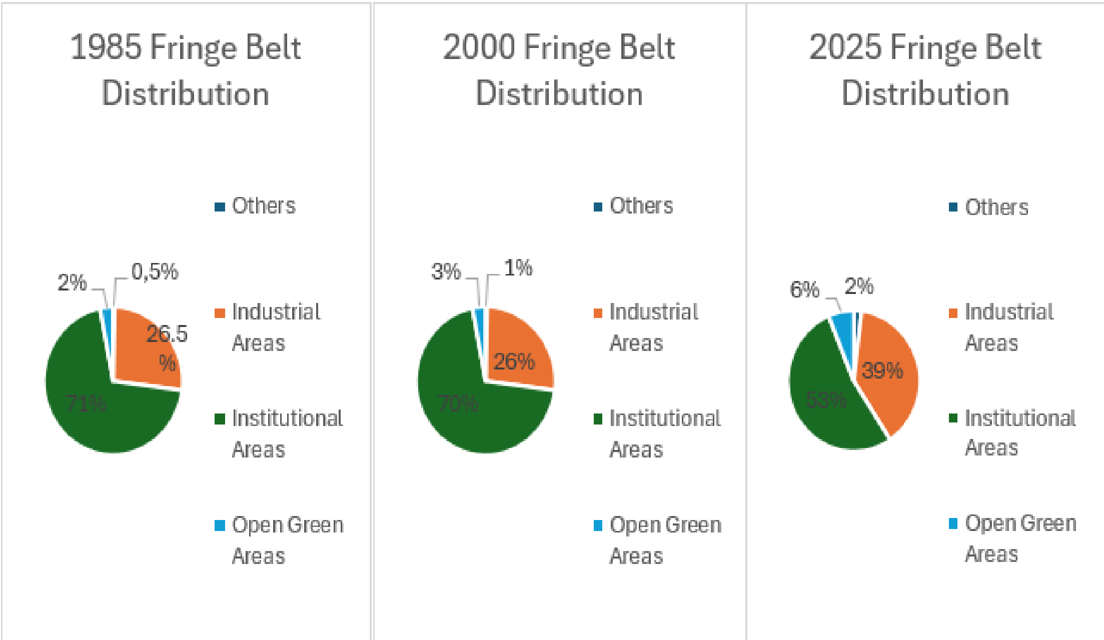

Figure 7 Distribution of FB plots over the years

3.3. Analysis of UHI Within FB Plots

In this study, the interaction between FB plots and surface UHI was assessed by overlaying normalized UHI data and FB vector data using the zonal statistics method, and the average UHI value was calculated for each FB plot. Consequently, the microclimatic characteristics of FB plots were quantitatively obtained, thereby revealing their heating or cooling effects within the city. In the cartographic documents created within the specified scope, the following colour-coding system was employed: "Very Cooling" (dark blue), "Cooling" (light blue), "Neutral" (yellow), "Warming" (orange), and "Very Warming" (red). The boundaries of residential areas were delineated in grey for each period.

It has been observed that areas within the city centre which have experienced a significant cooling effect tend to be located in proximity to green spaces, sports facilities, and institutional areas characterized by a high ecological capacity. Open spaces and parks, in particular, were identified as areas that reduced the UHI effect in the city centre. These areas, delineated in dark and light blue, were observed to have a cooling effect within the urban fabric. In a similar manner, public institutions with large permeable surface areas also exhibit a significant cooling effect. It has been established that such areas exert a positive influence on the microclimate, both within their own boundaries and in the surrounding areas.

The magnitude of the cooling effect increased in plots located in close proximity to the city centre between 1985 and 2000, owing to alterations in land use. Notwithstanding the occurrence of urban expansion, the cooling effect has been sustained as a consequence of the augmentation in the utilization of sports facilities and open green spaces. However, a marked increase in the proportion of plots categorized as "warming" or "very warming" has been observed in plots located to the east and west of the city center (Figure 8).

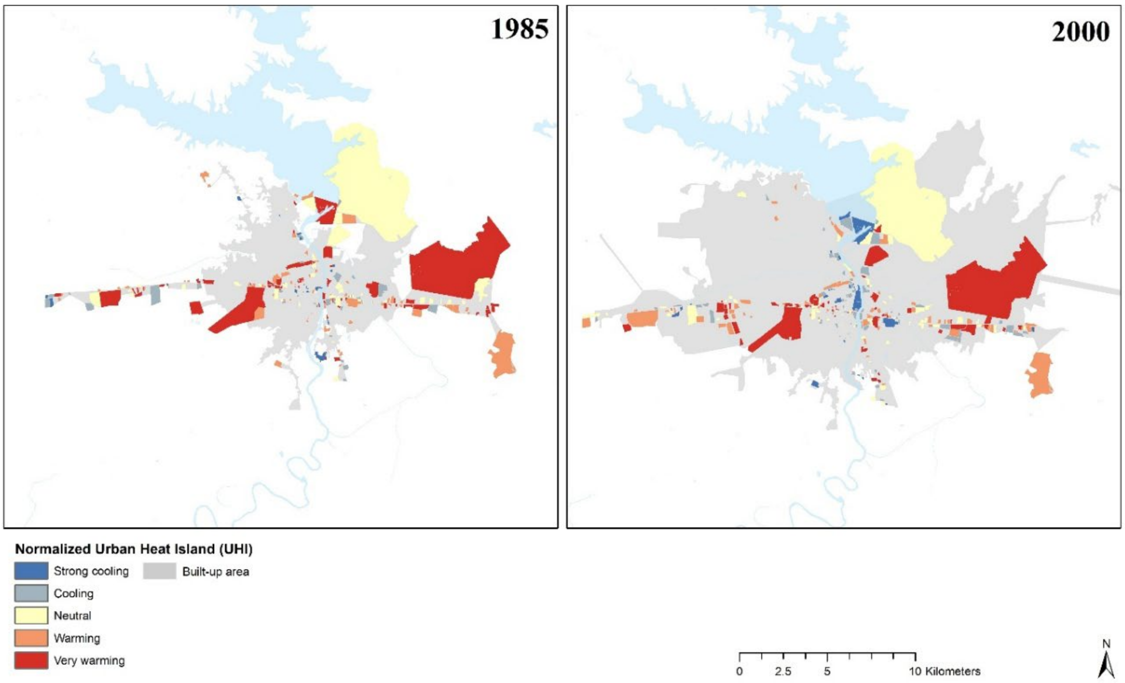

Figure 8 Spatial distribution of normalized UHI classes in 1985 and 2000

By 2025, there is an expectation of an increase in the UHI effect. In comparison with the year 2000, both the city centre and the peripheral areas located outside the city centre have experienced an increase in the categories of 'very warming' and 'warming'. The UHI effect has been observed to increase in the peripheral plots located on the southern and western peripheries of the city. Furthermore, the UHI effect formed during this period has contributed to an enhancement of this effect. While parks, institutional complexes, and sports facilities located in the city center remain the focal points of the cooling effect, the UHI effect stands out as the period during which it spread over the widest area in the analyzed years (Figure 9).

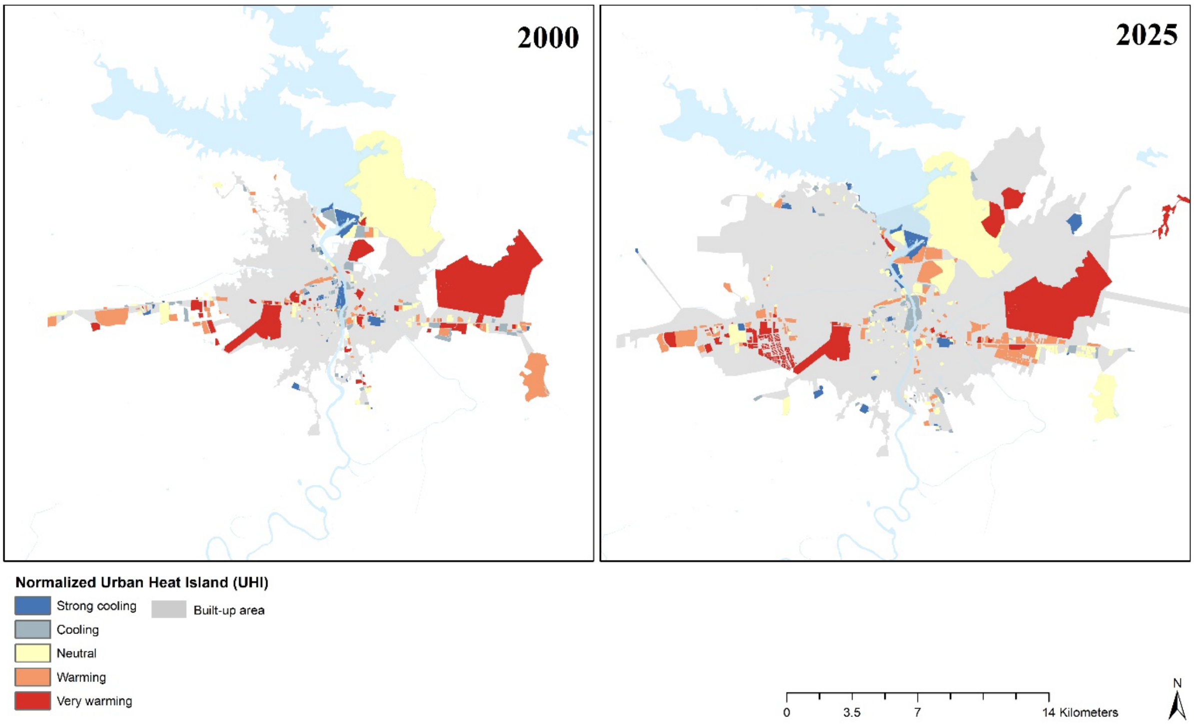

Figure 9 Spatial distribution of normalized UHI classes in 2000 and 2025

In 1985, 53.61% of fringe-belt plots were classified as "Warming", while the "Very Warming" class accounted for a mere 12.17% of the area. During this period, the total area exhibiting "Neutral" and "Cooling" effects exceeded 34%. This result suggests that fringe-belt areas exhibited greater resistance to the UHI effect in 1985, or alternatively, that these areas experienced less dense development.

A significant transformation is observed in 2025, with the proportion of areas classified as "Very Warming" increasing to 43.99%, while the proportion of areas classified as "Neutral" decreased to 6.73% and the "Cooling" class to 0.24%. This percentage change indicates that fringe-belt areas have undergone increased urbanization, with higher impervious surface ratios and significantly elevated surface temperatures. Nevertheless, this phenomenon suggests that certain marginal belts have transitioned from being transient to permanent, characterized by substantial heat accumulation.

The structural transformation observed between 1985 and 2025 demonstrates that urban sprawl is not merely a spatial expansion but also has profound effects on the thermal environment. In this context, the temporal analysis of the UHI effect on fringe belt areas is of critical importance for developing climate adaptation strategies in urban planning processes. Of particular note is the accelerated rise in the "Very Warming" category, which signifies the potential for exacerbation of the deleterious effects of these regions on ecosystem services and the loss of thermal comfort (Table 5).

Table 5 Proportion (%) of Fringe Belt Plots in Each Normalized UHI Class for the Years 1985, 2000, and 2025

Year	Very Cooling (%)	Cooling (%)	Neutral (%)	Warming (%)	Very Warming (%)
1985	0	2.2	31.94	53.6	12.17
2000	0	4.26	38.36	44.59	12.79
2025	0	0.24	6.73	49.04	43.99

The central question guiding this study, namely, "How has the spatial and structural transformation of FB areas during the urban development process affected the UHI effect?" has been largely addressed and validated by the study's findings. The hypothesis developed in this context suggests that the alienation, shrinkage, and increase in building density observed in fringe-belt areas alongside urban development contribute to the increase in the UHI effect by altering the thermal properties of these areas.

In the present study, the statistical significance of the relationship between UHI values and various land-use types (for example, open space, sports area, institutional area, etc.) in fringe-belt plots was analyzed using the Kruskal-Wallis H test. This non-parametric variance method is favored when data do not conform to a normal distribution and group sizes vary. For each year, the FB plots were classified according to the corresponding year's land use, and the Kruskal-Wallis test was employed to ascertain whether there was a significant difference between land use and UHI values. The fundamental hypothesis of the test is that the distributions of all groups are equivalent; a low p-value signifies a substantial discrepancy between at least two groups.

In the analysis conducted for 1985, $p=0.003$ ($p<0.05$) was obtained, indicating a significant difference between land use and UHI values. The statistical evaluation of land use and UHI for the year 2000 yielded $p < 0.001$, while for the year 2025, $p < 0.001$ was found.

In the evaluation of fringe-belt plots in 1985, 2000, and 2025, considering land use types, the mean, median, minimum, maximum, and standard deviation of UHI values and the number of plots were provided. In 1985, the areas with the highest average UHI values were found to be those designated for industrial land use (0.0142). The second-highest UHI values were exhibited by institutional areas (0.0106), followed by industrial areas. Conversely, open areas demonstrated the lowest UHI values (0.0093). Despite the relatively limited number of plots classified as "other", the average UHI value remained at an intermediate level of 0.0119.

In the year 2000, a substantial decline in UHI values was documented across all land use categories. Institutional areas exhibited an average UHI decrease to 0.0086, while open areas demonstrated a decline to 0.0031. Industrial areas, however, exhibited an increase to 0.0141. The relatively high UHI effect persists in industrial areas. However, the decline in the UHI effect in open areas suggests an augmentation in the cooling effect within the urban environment. In 2025, an increase in the UHI effect was observed again for all land use types, especially in industrial areas, where the average UHI rose to 0.022 and the maximum value (0.0348) remained quite high (Table 6).

Table 6 Descriptive Statistics of Normalized UHI Values by Land Use Type for 1985, 2000, and 2025

Year	Land Use	Number of Plots	Mean	Median	Min.	Max.	Std.
1985	Open Space	9	0.0093	0.0081	-0.0105	0.0289	0.0111
	Institutional	94	0.0106	0.0117	-0.0037	0.0239	0.0062
	Industrial	150	0.0142	0.0143	-0.0046	0.0324	0.0068
	Other	4	0.0119	0.0135	0.0021	0.0187	0.007
2000	Open Space	12	0.0031	0.0031	-0.0074	0.015	0.0064
	Institutional	11	0.0086	0.0089	-0.0053	0.0232	0.0052
	Industrial	165	0.0141	0.0143	-0.0051	0.0294	0.0068
	Other	3	0.0047	0.0033	0	0.0108	0.0056
2025	Open Space	43	0.0136	0.0142	0.0003	0.0251	0.0053
	Institutional	181	0.0181	0.0179	0.0062	0.0358	0.0048
	Industrial	180	0.022	0.022	0.0036	0.034	0.0061
	Other	12	0.0144	0.0155	-0.0009	0.0212	0.0062

A spatial evaluation indicates that fringe-belt plots displaying industrial usage demonstrate the highest mean UHI across all three designated periods. The cooling effect of institutional and open areas is maintained until 2000 but begins to be lost in 2025. Despite the limited number of plots classified as "other", a substantial increase in the UHI effect is evident by 2025 (Figure 10).

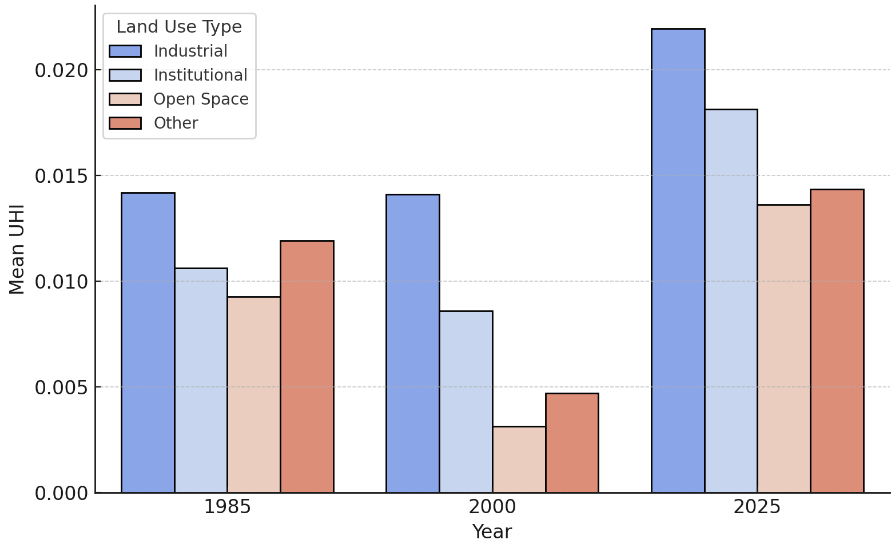

Figure 10 Mean UHI values by land use type (Industrial, institutional, open space, other) for 1985, 2000, and 2025

4. Discussion

The fringe-belt concept, which delineates morphological areas formed during historical urban growth processes and reflects urban development, also indicates that these areas should be reconsidered in urban planning not only for their physical but also for their environmental functions (Ünlü, 2022). The UHI effect, which has brought the increasing thermal pressure in urban areas to the forefront, highlights the microclimatic role of fringe-belt areas. However, a comprehensive study is absent from the extant literature that examines the direct relationship between the fringe belts and the UHI effect. This finding underscores the study's distinctive approach in evaluating fringe-belt areas at both the spatial and microclimatic levels.

In the relevant UHI literature, the principal strategies for reducing urban heat islands are listed as follows: increasing green space ratios, preserving permeable surfaces, reducing building density, and adopting street designs that support air circulation (Jusuf et al., 2007; Bhargava et al., 2017). However, the evaluation of such strategies is typically conducted through the utilization of green infrastructure elements dispersed throughout urban areas. Consequently, fringe-belt regions are not directly addressed within this context. However, fringe belts, due to their historical nature as permeable, green, or low-density areas in the peripheral lands of the city, have lower surface temperatures than city centers and thus have the potential to act as buffers against thermal stress.

Conversely, fringe-belt literature has focused predominantly on the examination of morphological continuity, functional transformation, and historical development periods. However, the recommendations available for the evaluation of these phenomena in planning remain limited. Recent studies have begun to define fringe belts not only as threshold areas but also as ecological and microclimatic green corridors. Hazar and Özkan's (2020) study emphasizes the role of these areas in terms of urban biophysical integrity, while Görgülü and Görgülü's (2021) study states that fringe belts should be evaluated as ecological thresholds that provide interrelationships between the built environment and natural systems. In his preliminary study on the ecological significance of fringe belts, Hopkins (2011) emphasized that these areas support biological diversity, provide ecosystem services, and connect urban natural areas. However, these approaches do not directly link the effects of fringe belts in the UHI context with data-based analyses.

This study is among the first to analyze fringe-belt areas by matching them with UHI effects, with a particular focus on Adana across three distinct periods. In the context of urban planning, fringe belts are regarded not only as spatial transition zones but also as microclimatic resilience points. These belts are considered strategic areas that can be utilized to reduce urban heat pressures. In this regard, the study serves to bridge the gap between the UHI and fringe belt literatures, offering a comprehensive framework that integrates these two approaches. From the perspective of urban planning, the proposal calls for the redefinition of fringe belts not only as areas earmarked for future development, but more significantly and crucially as components of climate-sensitive planning.

In this study, an examination of the period between 1985 and 2000 reveals that changes in land use in plots adjacent to the city centre have had a mitigating effect on the UHI effect. The augmentation in the prevalence of sports facilities, parks, and green spaces within the urban landscape, in conjunction with the proliferation of institutional areas in proximity to the city centre and the peripheral belt regions, has precipitated this outcome. The restructuring of institutional areas in their current locations, or the avoidance of intensive development in new institutional areas, may have been effective. This finding suggests that these areas have been effectively preserved in terms of their spatial integrity and that their cooling effects have been sustained despite urban expansion. Consequently, it can be posited that UHI pressure was constrained during this period. The area encompassing the fringe-belt region, which was 54.3 million m² in 1985, exhibited a 53% increase, reaching 83.3 million m² by 2025. However, this increase is not solely quantitative in nature; it also encompasses qualitative dimensions, including functional diversification, increased density, and structural alienation. The composition of fringe belts was initially dominated by institutional areas; however, these belts have gradually experienced increasing pressure from industrial, commercial, and high-density mixed-use developments. Consequently, they have undergone a significant shift in their original threshold functions. By 2025, industrial areas accounted for the largest share in fringe belts, indicating a reshaping of the periphery.

During the 2000–2025 period, the propagation of the UHI effect across a substantial geographical area is evident, encompassing both urban centers and peripheral suburban regions. It is evident that the increase in the "very warming" and "warming" categories in fringe-belt plots in the southern and western peripheries of the city is indicative of a disruption in the spatial continuity of these areas. This disruption suggests that these areas are subject to development pressure. As demonstrated in the study conducted by Zorlu and Söğüt (2019), utilizing the case study of Adana, following the year 2000, there has been a notable increase in urban density, particularly in threshold areas along the periphery. This phenomenon can be attributed to frequent alterations in master plan decisions, heightened development pressure through plan revisions, and the conversion of green areas into residential and mixed-use zones. This transformation has laid the groundwork for the disruption of not only the physical structure but also the microclimatic balance. In this context, the protection of fringe belt areas through sustainable planning decisions and their development using ecological planning approaches should be considered an important strategy for controlling the UHI effect.

UHI analyses have yielded definitive insights into the repercussions of this spatial transformation on the city's microclimate. In 1985, 34% of fringe-belt plots exhibited a cooling or neutral effect, while this rate fell below 7% in 2025. Concurrently, the proportion of areas classified as "Very Warming" exhibited a marked increase, rising from 12% to 44%. Industrial uses with high impervious surface ratios have consistently exhibited the highest UHI values in all three periods, while the cooling effect observed in open and institutional areas in 2000 began to weaken by 2025. Statistical analyses conducted on fringe-belt plots (Kruskal-Wallis H test) revealed significant differences between land use types and UHI values. The present study has revealed a significant increase in the UHI effect in industrial areas in 2025, whilst a decrease was observed in institutional and open areas. The findings demonstrate that structural transformation in fringe belts exerts not only functional but also climatic consequences, thereby causing the UHI effect to spread towards the city periphery.

5. Conclusion

The present study set out with the objective of unveiling the spatial and functional metamorphosis of fringe-belt areas in Adana between 1985 and 2025, whilst concomitantly analyzing the repercussions of this transformation on the UHI effect. A comparative analysis conducted over three periods reveals significant transformations in both size and quality in fringe-belt areas.

Consequently, fringe-belt areas have evolved from being merely urban threshold zones to becoming direct targets of urban pressures, intensification, and thermal stress. This transformation necessitates the re-evaluation of fringe belts as critical areas in urban planning processes, particularly in terms of climate adaptation, permeable surface conservation, and cooling area strategies. In this context, fringe-belt areas should be regarded not only as vestiges of historical urban form, but also as a high-priority component of climate-resilient urbanization policies in the future.

The findings reveal that the function of fringe-belt areas within cities has changed significantly over time and that this transformation has had a substantial impact on the thermal environment. The intensive development that has been observed in industrial areas, coupled with the increasing UHI effect, indicates that impermeable surfaces have increased and that green infrastructure is inadequate in these areas. In particular, by 2025, some fringe belt areas are expected to transform into areas with high thermal load accumulation and exposed to urban density pressure. This indicates that these areas are no longer merely transition zones but have become focal points of urban growth. This situation highlights the importance of incorporating fringe belt areas into future planning processes alongside climate adaptation strategies. It is evident that solutions such as the preservation and enhancement of the cooling effect of open and institutional areas, in addition to the integration of green corridors and heat-absorbing surfaces, can play a critical role in the balancing of the UHI effect in these areas. Moreover, the preservation of the functional diversity of fringe belt areas is of significance not only for microclimatic benefits but also for sustainable urbanization. In this context, planning policies must redefine fringe belts as spatial thresholds, establish specific land use decisions, and set development limits for these areas.

A comprehensive approach has been adopted to reveal the temporal change of fringe-belt areas, land use transformation, and their spatial relationship with UHI. However, in order to interpret the findings in greater depth, it is recommended that multivariate spatial statistical methods and advanced interaction models be used in future research. In particular, an examination of the structural relationships between the transformation of fringe-belt areas and urban dynamics, such as demographic structure, accessibility, property regime, and investment trends, will provide a more complex and meaningful analytical framework. The execution of comparative studies in cities exhibiting divergent climatic and morphological characteristics is of paramount importance for the elucidation of the universal principles that govern the fringe belt phenomenon, whilst concomitantly accounting for its site-specific variations. Furthermore, the increased precision afforded by high-resolution remote sensing data could facilitate more robust understanding of the temporal and spatial variations of the UHI effect. The development of scenario-based spatial simulations and decision support systems to test the effects of planning policies also presents a critical potential for future studies in terms of translating theoretical knowledge into practical applications.

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CRediT Authorship Contribution Statement

Gülnihal Kurt Kayalı: Writing – review & editing, Methodology, Investigation, Analysis. Büşra Gülbahar İşlek: Writing – original draft, Visualization, Data curation. Tuğba Akın: Writing – original draft, Visualization, Data curation. Tolga Ünlü: Conceptualization, Methodology, Writing – review & editing. Tülin Selvi Ünlü: Project administration, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

Data will be made available on request.

Ethics Committee Approval

Since this study does not involve human participants, animals, or any sensitive personal data, an ethics committee decision was not required, and this has been stated accordingly in the manuscript.

Resume

Gülnihal Kurt Kayalı is a landscape architect and researcher with a focus on Geographic Information Systems (GIS), remote sensing, and ecological landscape planning. She received her bachelor's and master's degrees in landscape architecture from Çukurova University, where she is currently continuing her doctoral studies. Her academic path has been shaped by an interest in understanding the interaction between urban development and natural systems, and by exploring methods that can contribute to more sustainable and resilient urban environments. Her research covers topics such as ecological networks, habitat connectivity, and urban resilience, with particular attention to how spatial data and landscape metrics can inform planning decisions. She has contributed to different research projects and has presented her studies in national and international academic settings. These experiences have supported her interest in applying interdisciplinary approaches and technology-based methods to issues of urban and environmental sustainability. She continues her academic work with the aim of combining scientific analysis and practical perspectives to support more balanced relationships between cities and natural landscapes.

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