

Spatial Evaluation of Urban Green Space-Population Relationship Using Sentinel-2 Satellite Data and Object-Based Image Analysis: A Case Study Antalya

Mesut ÇOŞLU^{1*} 

¹Burdur Mehmet Akif Ersoy University, Science and Letters Faculty, Precision Agriculture and Agricultural Robots Department, Burdur, Türkiye
Mesut ÇOŞLU ORCID No: 000-0003-3952-6563

*Corresponding author: mcoslu@mehmetakif.edu.tr

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Abstract: The relationship between urban green space (UGS) and population is essential for the quality of life in cities. This study proposes a method to determine the relationship between UGS and population in Antalya, Türkiye, and to assess short-term changes, using Sentinel-2 satellite data and object-based image analysis (OBIA). In the study, two different dated Sentinel-2 data were utilized as the basic data set to analyze the vegetation. The Normalized Difference Vegetation Index (NDVI) was calculated for the threshold value and UGSs were analyzed according to different categories. Then, the Urban Green Space Index (UGSI) was computed to determine the amount of green space and Per Capita Green Space (PCGS) was also computed for this purpose. The OBIA general accuracy values of the proposed method are 93% and 94% for 2017 and 2023, respectively. The results showed that PCGS across the study area decreased by 7.33 m² in a short time. It is evaluated that the method proposed in this study, which reveals the short-term change in UGS and PCGS more quickly and at lower cost, can be used effectively in sustainable city management.

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Sentinel-2 Uydu Verileri ve Nesne Tabanlı Görüntü Analizi Kullanarak Kentsel Yeşil Alan-Nüfus İlişkisinin Mekânsal Değerlendirilmesi: Antalya Örneği

Anahtar Kelimeler

Peyzaj,
NDVI,
OBIA,
KBYA,
Uzaktan Algılama ve CBS

Öz: Kentsel yeşil alan (KYA) ile nüfus arasındaki ilişki, kentlerdeki yaşam kalitesi için önemlidir. Bu çalışmada, Türkiye, Antalya'da KYA ile nüfus arasındaki ilişkiyi belirlemek ve kısa dönemdeki değişimi ortaya koymak için Sentinel-2 uydu verileri ve nesne tabanlı görüntü analizi (OBIA) kullanılarak bir yöntem önerilmiştir. Çalışmada bitki örtüsünü analiz etmek için iki farklı tarihli Sentinel-2 uydu görüntüsü temel veri seti olarak kullanılmıştır. Eşik değeri için Normalize Edilmiş Fark Bitki Örtüsü İndeksi (NDVI) hesaplanmış ve KYA'lar farklı kategorilere göre analiz edilmiştir. Ardından, yeşil alan miktarını belirlemek için Kentsel Yeşil Alan İndeksi (KYAI) ve aynı zamanda Kişi Başına Yeşil Alan (KBYA) da hesaplanmıştır. Önerilen yöntemin OBIA genel doğruluk değerleri 2017 ve 2023 yılları için sırasıyla %93 ve %94'tür. Sonuçlar, çalışma alanı genelinde KBYA'nın kısa vadede 7.33 m² azaldığını göstermiştir. KYA ve KBYA'da kısa vadeli değişimi daha hızlı ve daha düşük maliyetle ortaya koyan bu çalışmada önerilen yöntemin sürdürülebilir kent yönetiminde etkin bir şekilde kullanılabileceği değerlendirilmektedir.

1. INTRODUCTION

A Remote sensing (RS) technology is an important tool for monitoring the current status and dynamics of vegetation ecosystems [1]. With the developing technology, there have been significant developments both hardware and sensor technologies in satellite systems that provide data for RS. In this context, satellite systems with higher spatial, radiometric, spectral and temporal

resolution have increased the use of this technology in Earth observation studies. Temporal resolution, especially expressed as revisit time, is essential to detect change in agriculture, forest and urban areas and to provide a rapid response to this change. Nowadays, many companies offer systems with high-resolution RS data for a fee. However, the European Space Agency (ESA) offers free data access with multispectral (MS) instruments such as

Sentinel-2, which have high spatial (10 m), temporal (5 days) resolution and wide coverage area [2-4].

Urbanization causes changes in surface materials due to reasons such as suppression of vegetation and a decrease in soil permeability. Variations in the energy reflected from the surface in urban areas cause higher temperatures relative to rural areas, contributing to the formation of an urban heat island, which represents an anthropogenic change [5, 6]. In addition, urban growth causes changes in land use and land cover (LULC) in many areas around the world, especially in developing countries [7]. One of the most important effects of urbanization is that it poses a threat to the use of agricultural lands. Depending on the LULC, this may cause agricultural lands to change or even disappear [8].

Urban green space (UGS), an essential element of urban environmental systems, is the structure consisting of various vegetation types that have diverse social functions and are associated with urban land use types [9, 10]. UGS, which plays a crucial role in maintaining ecological balance and supporting human health, is essential for improving air quality for urban residents and encouraging greater physical activity, reducing the negative effects of urbanization and promoting the sustainable growth of urban ecology [11]. Recent studies have revealed that the coronavirus pandemic (COVID-19), which emerged in late 2019, may have significant physical and mental effects on human health. The restrictions imposed during COVID-19 have especially increased people's desire to access UGS [12].

Effective management and planning of UGS are essential to fully realize their advantages for both urban residents and the urban ecosystem in general. Nonetheless, inventorying urban vegetation through traditional methods is expensive and requires a significant amount of time. [17]. In this context, studies such as monitoring and determining temporal changes in LULC in urban areas using RS and geographic information systems (GIS) technologies [18, 19], urban planning and environmental management [20], land cover classification and coastal spatial planning [21] and analysis of the impact of urbanization on urban agriculture [8] can be carried out both at lower cost and with less labor in a shorter time.

One of the most important developments in RS technology, which is closely related to urban science, is object detection using RS data [22]. OBIA, which identifies image objects that are neighboring pixel groups and is used for object detection in RS, is a very useful method for image classification [23]. Studies carried out in urban areas with OBIA include monitoring urban tree cover [24], determining urban tree species and mapping carbon stocks for urban green planning and management [25], evaluating small UGS with OBIA and the vegetation index [26] and analyzing how UGS affect the health of the city's residents [27]. Pouya and Aghlmand [12] used RS and GIS technology to evaluate PCGS according to the population of neighborhoods in the Battalgazi District of Malatya Province and revealed that existing UGSs are not distributed equally across neighborhoods. Ortçeşme et al. [28], who investigated the situation of Antalya's active

green areas comprehensively, used zoning plans and the explanation reports for these zoning plans. The findings obtained by the researchers showed that active green areas are insufficient and irregular throughout the city. In another study carried out in Antalya, Manavoğlu and Ortçeşme [29] developed a proposal for a green space system in the Konyaaltı urban area. In another study, Manavoğlu and Ortçeşme [30], examined open and green areas with the help of Landsat satellite data and multi-criteria analysis. Researchers have found that active green spaces are unevenly distributed; however, their overall presence is on the rise.

The primary aim of this study is to assess UGS in terms of quantity and quality with RS data, GIS and OBIA method. In the study, Sentinel-2 images were used as RS data to determine LULC. LULC classes in the study area consist of UGSs (landscape, forest and agricultural areas) and impervious surfaces (buildings, roads, etc.). With the findings obtained from the UGSI and PCGS values calculated within the scope of the study, the short-term change in UGS was revealed and thus it is aimed to contributing to urban planning.

2. MATERIAL AND METHOD

2.1. Material and Method

The research was conducted in Antalya Province, located in southern Türkiye, a region known for its significance in both agriculture and tourism. The study was conducted in Muratpaşa District, one of the central districts with the largest population of Antalya (Figure 1). Muratpaşa, the oldest settlement in Antalya, has a 20 km coastal strip. The Mediterranean Sea is in the south of Muratpaşa, Kepez District in the north, Konyaaltı District in the west, and Aksu District in the east [31]. Although the study area, which includes the International Antalya Airport and tourist facilities, has a dense urban area, there are also landscape areas, forest areas and agricultural production areas. The average temperature of the study area, where the Mediterranean climate is observed, in the long-term (1930-2023) was recorded as the lowest in January (10.0 °C) and the highest in July (28.4 °C) [32].

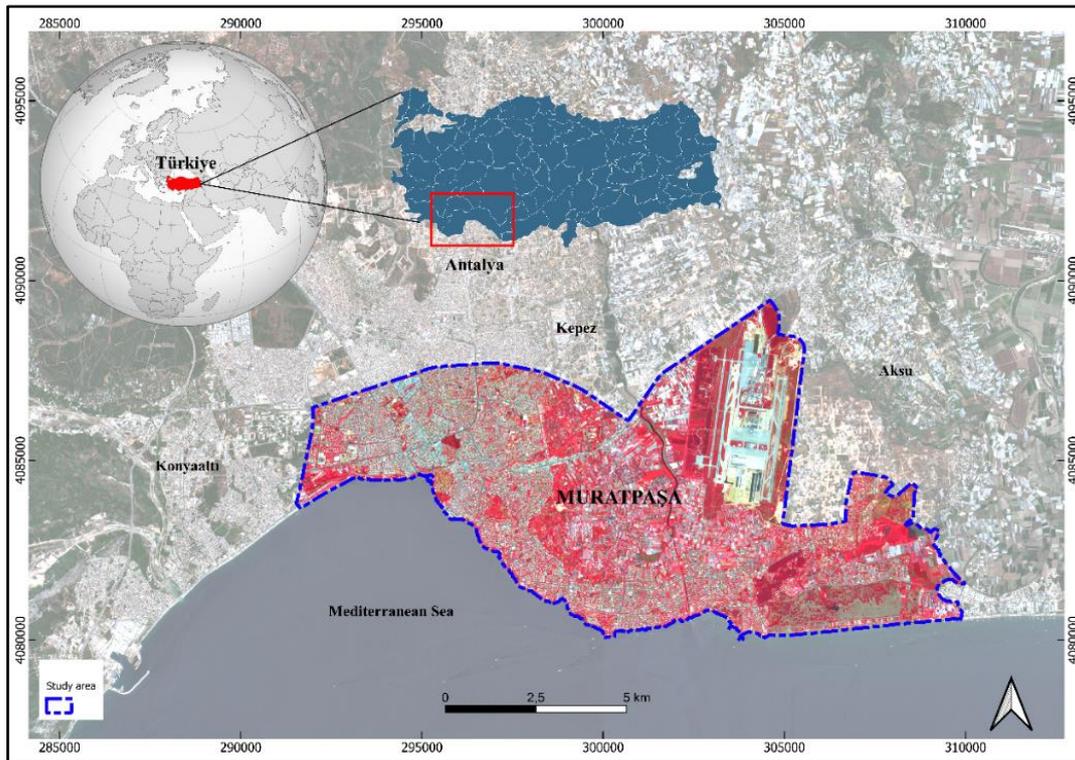


Figure 1. Study area

- i) it is one of the central districts with the largest population,
- ii) the change in population during the specified dates is the lowest compared to other districts,
- iii) it has an old and dense urban area.

2.2. Satellite Data

Sentinel-2 is a wide-coverage, high-resolution, MS imaging mission that is supporting Copernicus land monitoring efforts. Sentinel-2 satellites, which have 13 spectral bands, are used in monitoring vegetation, forest, soil and water surfaces [33] (Table 1).

Table 1. Bands of Sentinel-2 [34]

Band	Band name	Central Wavelength (nm)	Spatial Resolution (m)
1	Coastal aerosol	443	60
2	Blue	490	10
3	Green	560	10
4	Red	665	10
5	Vegetation red edge	705	20
6	Vegetation red edge	740	20
7	Vegetation red edge	783	20
8	NIR	842	10
8A	NIR	865	20
9	Water vapour	940	60
10	SWIR-Cirrus	1375	60
11	SWIR	1610	20
12	SWIR	2190	20

nm: Nanometer, m: Meter, NIR: Near Infrared, SWIR: Shortwave Infrared

In this study, the 10 m spatial resolution Blue, Green, Red and NIR bands of the Sentinel-2 satellite for 2017 and 2023 were used (Figure 2).

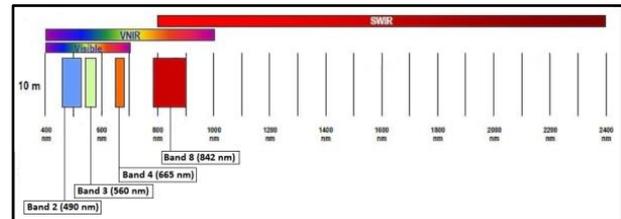


Figure 2. 10 m spatial resolution bands [34]

2.3. Demographic Data

The demographic data utilized in the study are population data and were sourced from the Turkish Statistical Institute (TSI). As part of the study, the population data of all districts of Antalya between 2017 and 2023 were arranged and those of Muratpaşa for 2017 and 2023 were filtered (Appendix A).

2.4. Methodology

This study includes the key steps of acquisition of Sentinel-2A images, demographic data, district and neighborhood boundaries, pre-processing, OBIA and evaluation of analysis results with population data (Figure 3). eCognition (Trimble Inc., Sunnyvale, CA, USA) software was used in the OBIA stage of the study, and ArcGIS (ESRI, California, USA) software was used to transfer and evaluate the analysis results in the GIS environment.

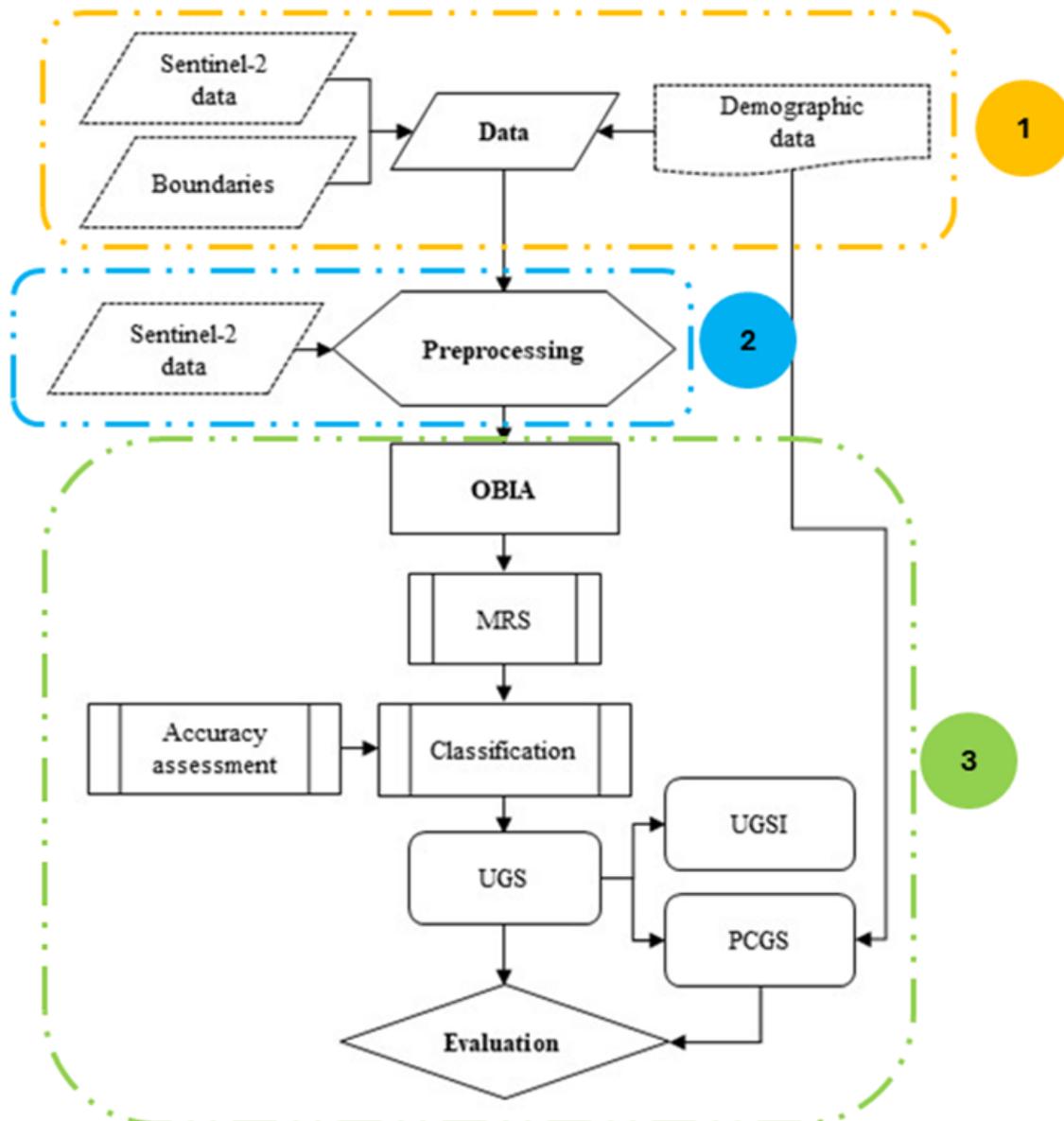


Figure 3. General workflow of the study

During the data acquisition stage, Sentinel-2 data were obtained from the Copernicus Open Access Hub. The study utilized data starting from 2017, as the earliest Sentinel-2 satellite images for the region achieved sufficient quality and temporal consistency from that year onward. The year 2023 was chosen as the endpoint to capture short-term variations and to encompass a complete vegetation cycle within the study period. Considering the cloudiness and greenness of the vegetation in the study area, June was determined as the most suitable month for both years. In this context, data dated 26 June 2017 and 15 June 2023 were used in the study. The data provided for these dates are Level-2A data, which are atmospherically corrected surface reflectance data obtained from Level-1C products. Atmospheric correction of Sentinel-2 data involves correcting the scattering of air molecules, atmospheric gases especially such as ozone, oxygen, and water vapor, and absorption-scattering effects caused by aerosols [35]. During the preprocessing stage of Sentinel-2 satellite data, band composition, merging of image frames and clipping according to the boundaries of the study area for 10 m

spatial resolution bands were performed. In addition, the projection and datum information of the vector data which contains the study area boundary used at this stage were reprojected according to Sentinel-2 data.

The OBIA method was used to analyze Sentinel-2 data. OBIA consists of two basic stages: segmentation and classification. During the segmentation phase, the multiresolution segmentation (MRS) algorithm was applied, and the threshold value classification method was used in the classification stage. The most important stage of OBIA is segmentation. When sample areas at different dates in the study area were examined, it was determined that scale parameter values below 30 (10 and 20) caused over-segmentation while values above 40 caused under-segmentation. In this context, the most appropriate scale parameter value for both years was determined as 30, and the composition of the homogeneity criterion (shape and compactness) was determined as 0.1 and 0.5, respectively. To determine green spaces, three classes were created during the classification stage: non-vegetation (NV), low vegetation (LV) and high vegetation (HV) Hashim et al. [36]. Among these classes, NV encompasses barren areas,

built-up areas, and road networks; LV comprises shrub and grassland; and HV includes urban forest areas. Additionally, NDVI, which will be used as a threshold value, was calculated at this stage. NDVI is an analysis method that can be used to monitor the density and health status of vegetation in an area [37]. NDVI takes a value between -1 and +1. While NDVI approaching +1 means that the vegetation in the area is dense or healthy, approaching -1 means that the vegetation is relatively sparse, unhealthy, or even indicates lack of vegetation in the area depending on its value. Aryal et al. [38] stated that the use of NDVI was acceptable in the study of mapping green areas in an urban area. In this context, NDVI was calculated using Equation 1 to determine the UGS in the study area [39].

$$NDVI = \frac{R_{NIR} - R_{Red}}{R_{NIR} + R_{Red}} \quad (1)$$

where R_{NIR} refers to the reflection in the NIR region and R_{Red} refers to the reflection in the red region.

In this study, NDVI threshold values recommended in previous studies were used [36, 39]. An error matrix based on the samples was used to evaluate the results of the classification stage in OBIA. In the accuracy evaluation, a total of 100 sample objects were selected for three classes, considering their distribution in the study area.

The Urban Green Space Index (UGSI) given in Equation 2 was used to determine the UGS in the study area [40].

$$UGSI = \frac{G_i}{A_i} \quad (2)$$

where G_i , green space area and A_i , total area.

The average amount of green space per capita was calculated using Per Capita Green Space (PCGS) given in Equation 3 [40].

$$PCGS = \frac{G_i}{P_{Ni}} \quad (3)$$

where G_i , total green space in i and P_{Ni} , total population in i .

3. RESULTS AND DISCUSSION

Based on the address-based population registration system (ABPRS), the total population of the five districts comprising the center of Antalya is 1,489,792. This population corresponds to 55% of the total population of Antalya. This means that one in two people in Antalya lives in one of these districts.

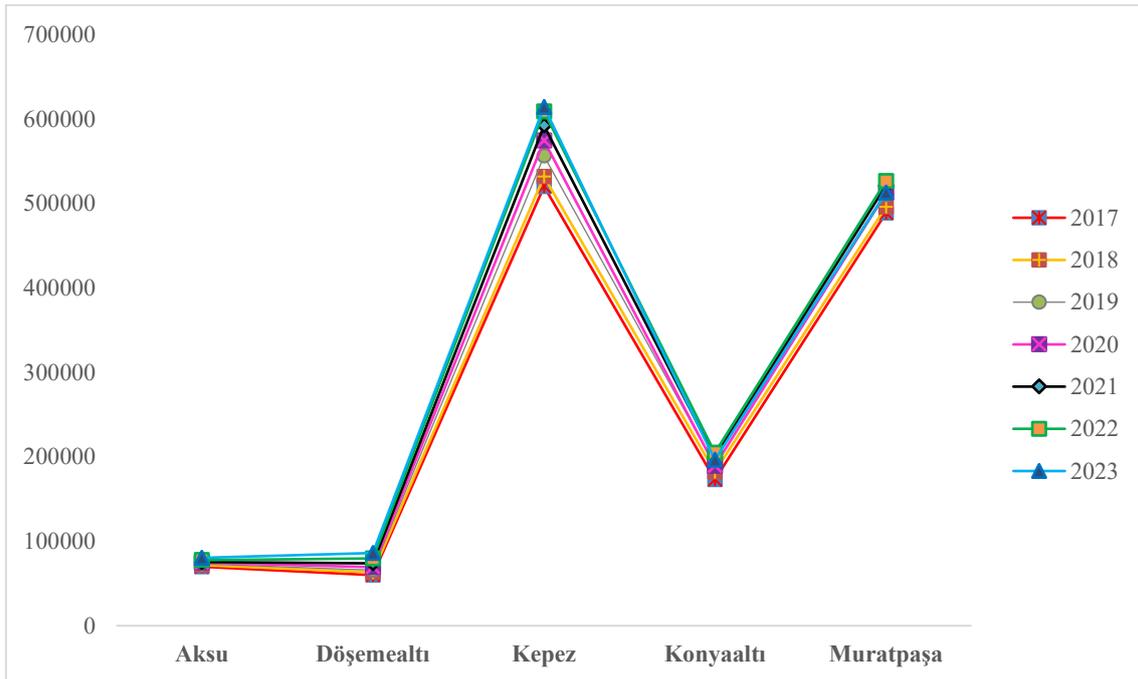


Figure 4. 2017-2023 population data of the five districts

From 2017 to 2023, which includes the study period, the population growth rate was highest in Döşemealtı District (44%) and lowest in Muratpaşa District (5%) (Figure 4). According to the results of the segmentation process performed at four scale levels in OBIA for 2017 (L1: 10, L2: 20, L3: 30, L4: 40), 514958 objects at L1, 135073 objects at L2, 58281 objects at L3 and 33321 objects at L4 were extracted. According to the results of the segmentation process carried out for 2023, 503286 objects

at L1, 130635 objects at L2, 56477 objects at L3 and 32320 objects at L4 were extracted. The result of the segmentation process at different levels for a sample area for 2023 is seen in Figure 5. Determining the appropriate parameters and criteria during the segmentation process of the OBIA method, which is very advantageous in extracting information from high spatial resolution data, by trial and error, requires expertise and prolongs the processing time [41, 42, 21].

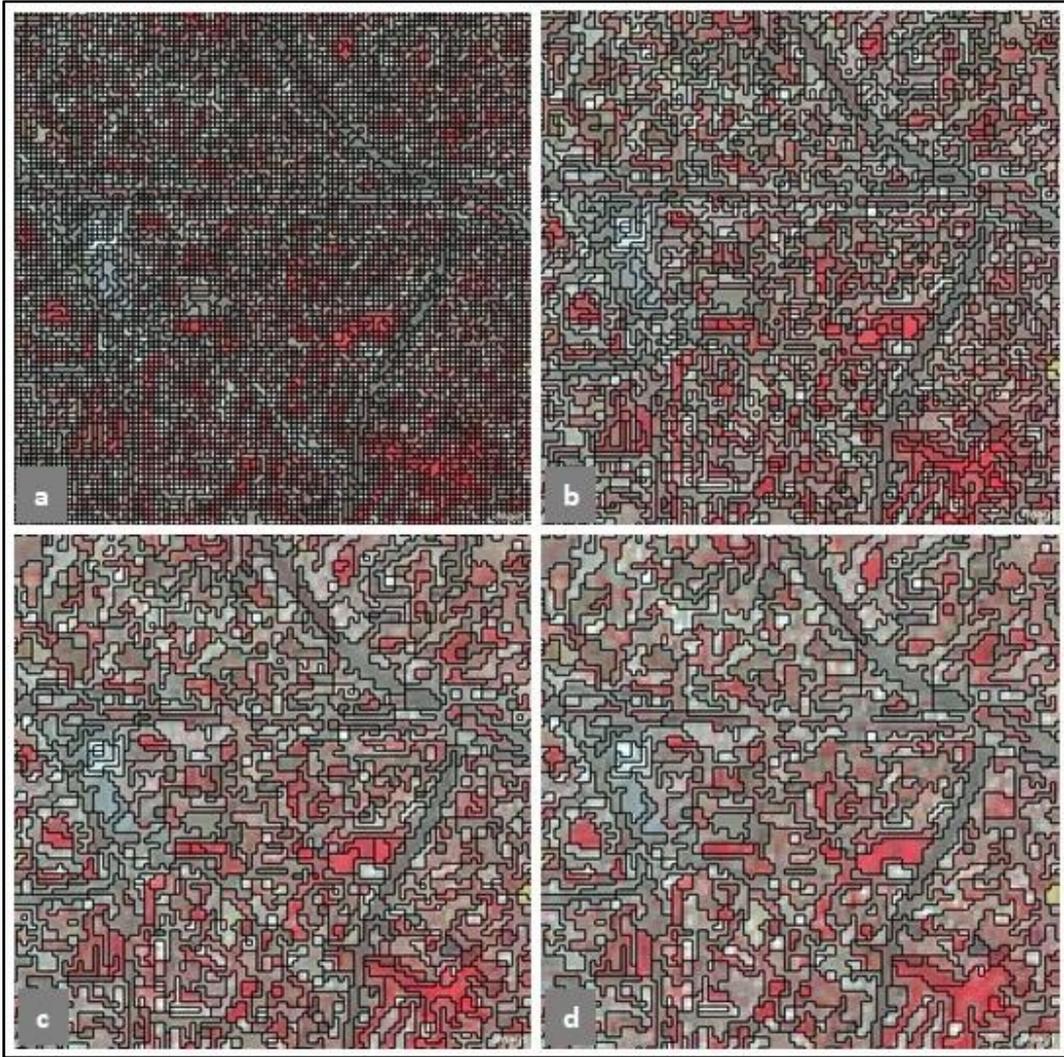


Figure 5. Results of the segmentation process: (a) L1, (b) L2, (c) L3 and (d) L4

According to the accuracy evaluation results of OBIA, high overall accuracy (OA) values and kappa statistics were obtained for both years. For 2017, the OA value is 93% and the kappa statistic is 0.88, and for 2023, the OA value is 0.94 and the kappa statistic is 0.90. The accuracy assessment results demonstrated that the proposed method was effective in identifying UGS. The results were determined to be quite high, similar to the findings in the study by Shekhar and Aryal [40] in which UGS was determined using GeoEye satellite data and OBIA. Zaki et al. [21], used Sentinel-2 data and the OBIA method, and

producing similarly high OA values compared to previous studies. The results of the classification process obtained from OBIA were transferred to the GIS environment to map UGS and calculate UGSI and PCGS (Figure 6). According to the OBIA results obtained from the study, in Muratpaşa, one of the most populous and densest urban areas of Antalya, the NV area for 2017 is 45.72 km², LV area is 36.15 km² and HV area is 7.16 km², and the NV area for 2023 is 47.32 km², LV is 38.22 and HV is 3.49 km². These findings showed that NV and LV areas increased slightly from 2017 to 2023 while HV areas decreased.

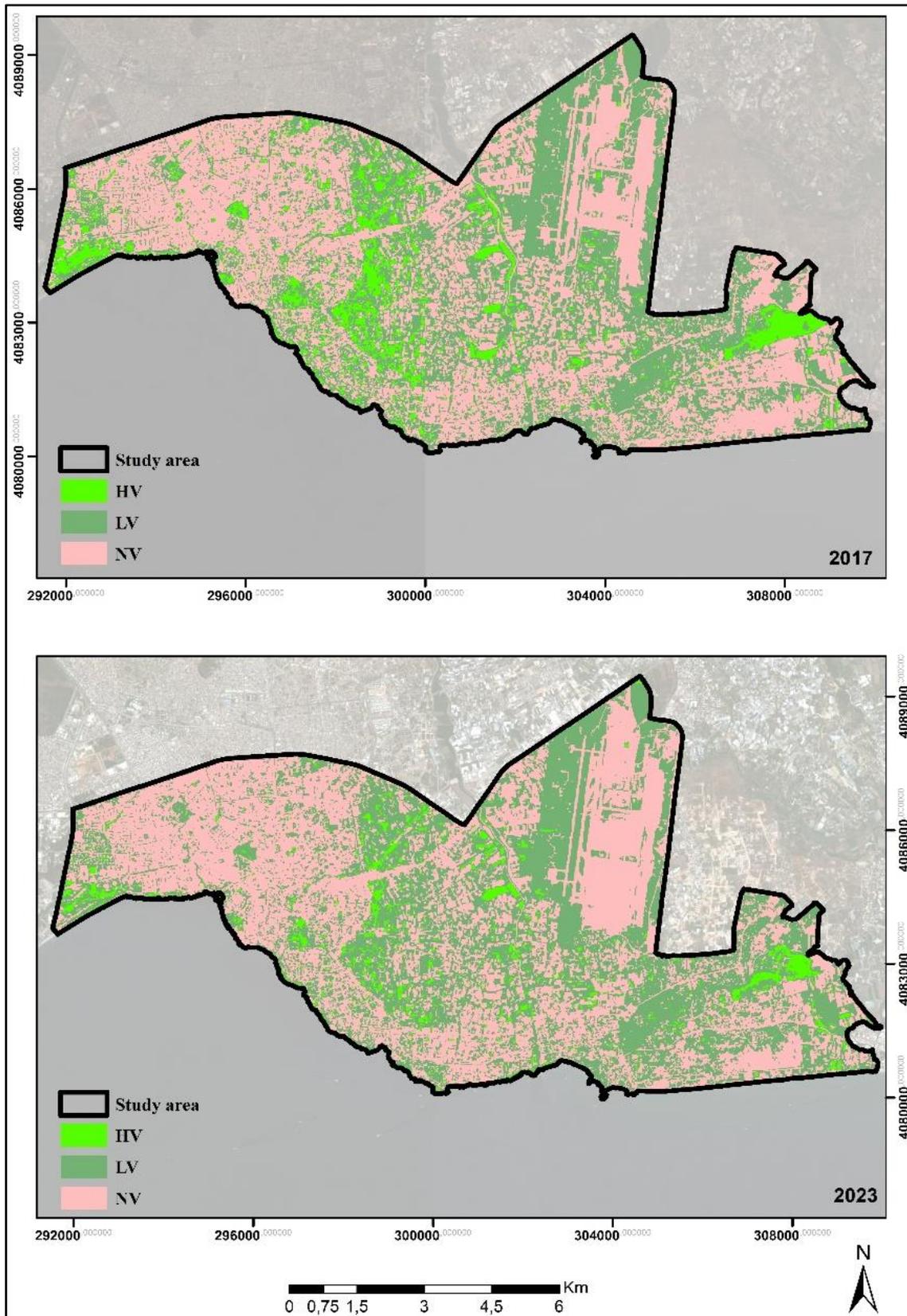


Figure 6. Results of OBIA (UGS)

In Muratpaşa, where the total UGS amount for 2017 is 43.31 km², the UGSI value is 48.65% (40.60% LV and 8.05% HV) and the PCGS value is 88.68 m². The total amount of UGS for 2023 is 41.71 km², the UGSI value is 46.85% (42.93% LV and 3.92% HV), and the PCGS value is 81.35 m² (Table 2). Findings show that PCGS values in Muratpaşa in both years are above Türkiye's minimum

(>10 m²), WHO's minimum (>10 m²) and ideal (>50 m²) values. In the study conducted by Manavoğlu and Ortaçşme [30], when the ratio of active green areas to the total area of the districts throughout Antalya was examined, it was determined that Muratpaşa had a higher ratio than the others. In the study conducted by Pouya and Majid [2022] in another city of Türkiye, PCGS values were found to be above the minimum values specified by

both Türkiye and the WHO. It was determined that the population in Muratpaşa increased by only 2658 people compared to the previous year (2019), especially in 2020, when COVID-19 restrictions began, and it increased by 8144 in 2021 and 5114 in 2022 but decreased by 13564 people in 2023. In this period (2017-2023), it was

determined that the population, which fluctuated in the short-term due to both COVID-19 and other factors, increased by 24308 people and the change in UGSI was only 1.8%. The findings obtained from this study showed that PCGS decreased by 7.33 m² in Muratpaşa over the period from 2017 to 2023.

Table 2. UGSI and PCGS on different dates

Year	Area (km ²)	Population	Non-Vegetation (km ²)	Vegetation(km ²)	UGSI (%)			PCGS*
					None	Low	High	
2017	89.03	488392	45.72	43.31	51.35	40.60	8.05	88.68
2023	89.03	512700	47.32	41.71	53.15	42.93	3.92	81.35

*m² per capita

The method proposed in this study, which involved determining the changes in UGS and PCGS on different dates throughout Muratpaşa, was also evaluated separately in 55 neighborhoods of Muratpaşa (Figure 7). There are different regions in terms of the urban area, green area and demographic structure. For example, the

largest neighborhood in terms of area is Yenigöl (17.4 km²), where Antalya Airport is also located, while the most crowded neighborhood in terms of population is Güzeloba (37074). UGSI values for all neighborhoods in the study area for 2017 and 2023, PCGS values are given in Appendix B and, Appendix C.

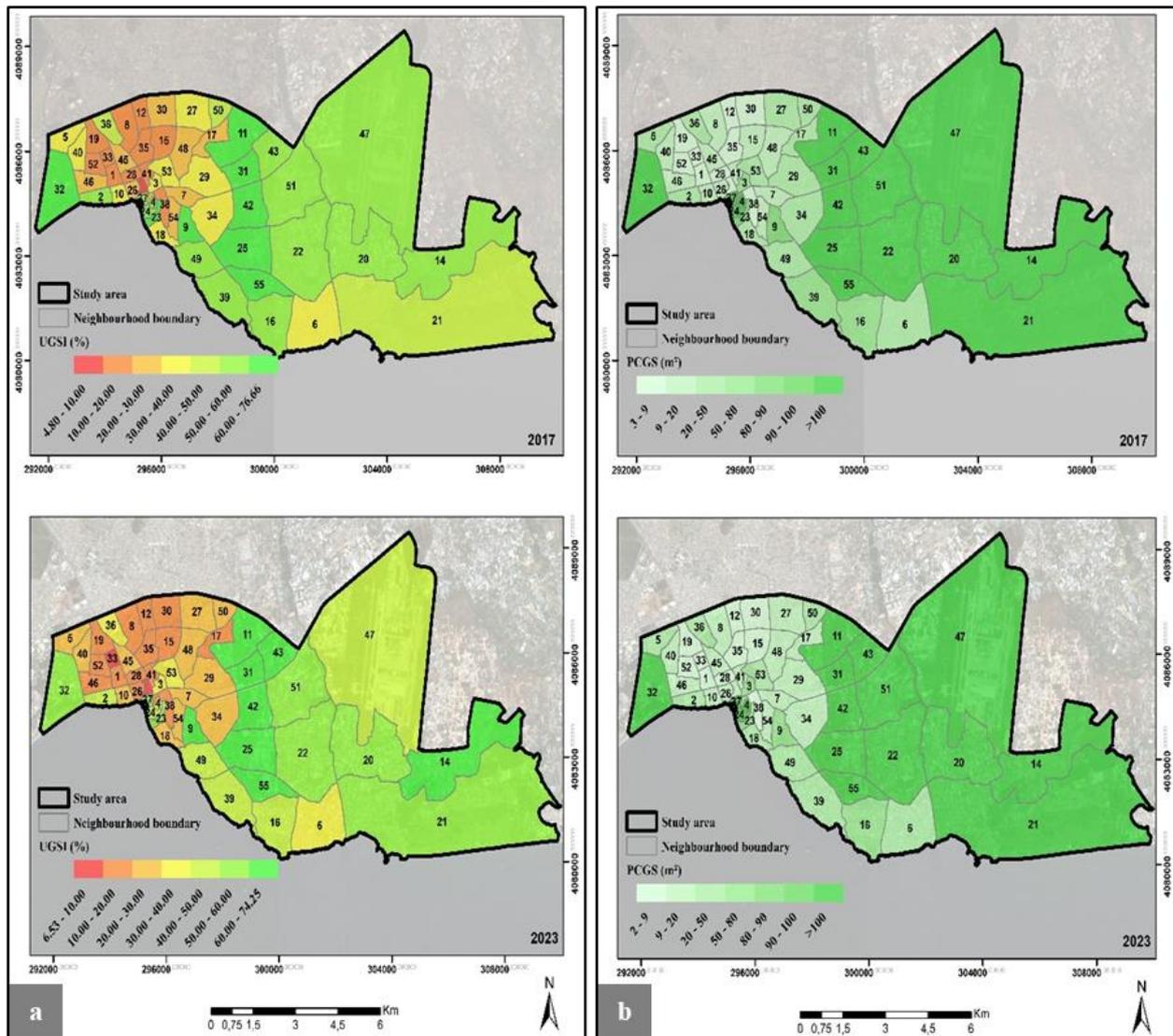


Figure 7. Results of UGSI and PCGS: (a) UGSI and (b) PCGS

The average UGSI values of all neighborhoods in Muratpaşa for 2017 and 2023 are 39.34% and 34.53%, respectively. Accordingly, it was determined that there

was a 4.31% decrease in the average UGSI. For 2017 and 2023, the lowest UGSI (4.80% and 6.53%, respectively) was calculated for Elmalı neighborhood (ID: 13), and the highest UGSI (76.66% and 74.25%, respectively) was

calculated for Mehmetçik neighborhood (ID: 31). In the study area, the region where the change in terms of UGSI is seen the most (from 58.17% to 31.81%) is Barbaros neighborhood (ID:04), while the region where the change is seen the lowest (from 12.76% to 12.42%) is Altındağ neighborhood (ID:01) (Figure 8a and Appendix B). It was determined that there were slight increases in UGSI in some regions (10 neighborhoods). Accordingly, it was

determined that the regions where the UGSI value increased the most were Ermenek (ID: 14) and Topçular (ID: 43) neighborhoods, and the UGSs in these areas were generally comprised mostly of agricultural areas. In addition, according to the study's findings, it was determined that some areas with an increase in UGS (such as airports and agricultural zones) were either not public spaces or consisted primarily of agricultural regions.

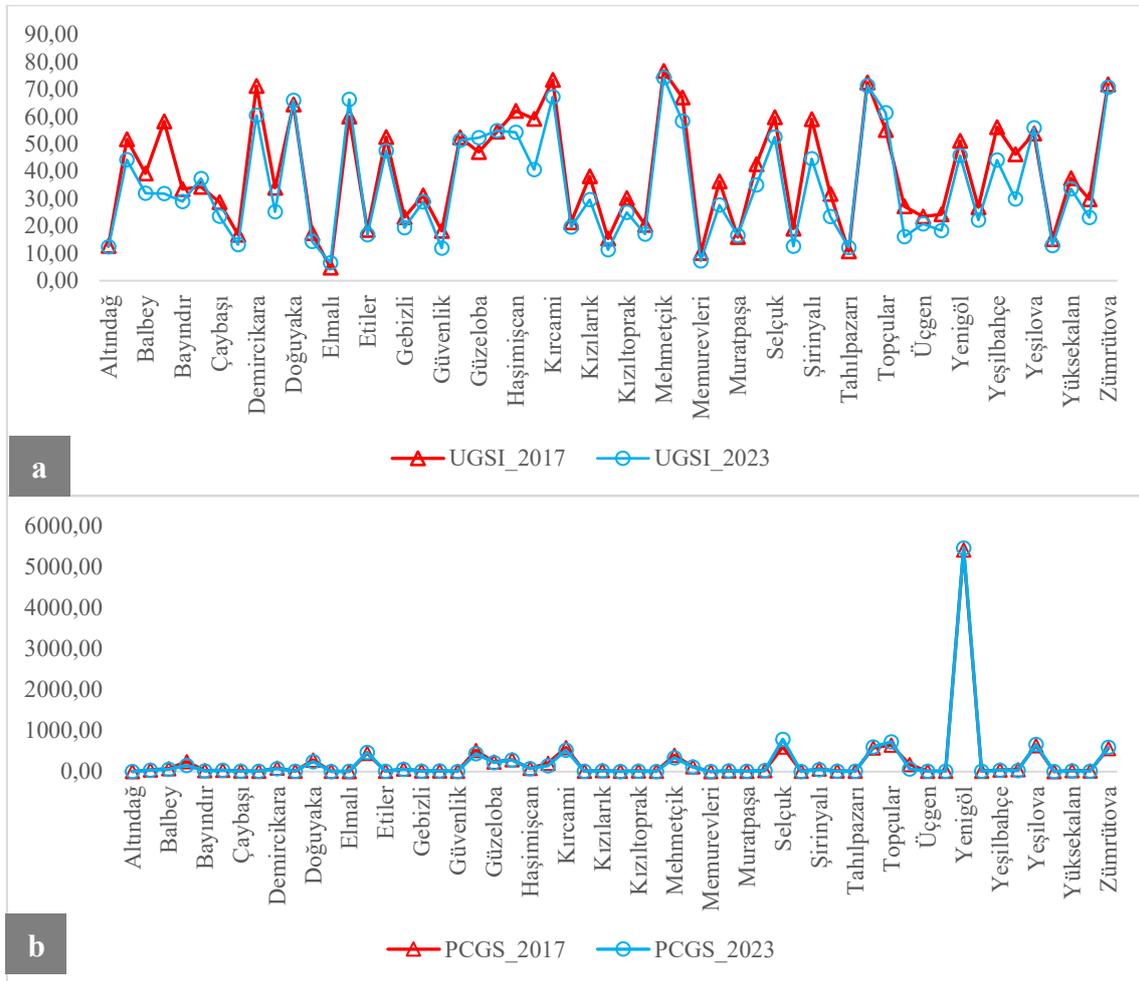


Figure 8. Change of UGSI and PCGS from 2017 to 2023: (a) UGSI and (b) PCGS

The average PCGS values for 2017 and 2023 are 234.32 m² and 229.10 m², respectively. Consequently, it was found that the average PCGS values were both very similar and relatively high. For 2017 and 2023, the lowest PCGS (2.69 m² and 2.06 m², respectively) was calculated for Memrevleri neighborhood (ID: 33), and the highest PCGS (5402.25 m² and 5448.43 m²) was calculated for Yenigöl neighborhood (ID: 47). The reason why the highest PCGS values are in Yenigöl neighborhood and the average PCGS values in Muratpaşa are high is that Antalya Airport is in this neighborhood (low UGS, high population). When Figure 8b, which is showing the change in PCGS and Appendix C are examined, it is seen that 45 out of 55 neighborhoods are above the minimum PCGS value determined by WHO, and 43 are above the minimum value determined by Türkiye for 2017. For 2023, while the number of neighborhoods above the WHO minimum value was 45, the number of neighborhoods above the minimum value determined by Türkiye was 42. In addition, while there were 22

neighborhoods above WHO's ideal PCGS value for 2017, this number decreased to 21 neighborhoods due to the change in Şirinyalı neighborhood (ID: 39) for 2023.

UGS serves as a valuable data source for tracking and evaluating urban environments as well as analyzing ecological services. Satellite RS technology makes significant contributions to long-term and large-scale monitoring of spatiotemporal changes in UGS models [43]. Additionally, as stated by Zhu and Ling [44], spatiotemporal changes have important advantages for landscape and urban planning. Although there has been a slight decrease in UGSI and PCGS both in Muratpaşa and on a neighborhood basis in the short-term, it should not be ignored that the UGS in this area is on decreasing trend, and there may be changes in other UGSs in the long-term. One of the most important issues within the scope of UGS is the rapid and uncontrolled urbanization, which is one of the main reasons for the loss of UGS in urban areas. This situation creates great pressure on the urban environment, and as a result, the quality of urban life gradually

decreases [9]. In this context, one of the most crucial issues is the division of open spaces and UGSs in urban areas into smaller pieces. Zhu and Ling [44] revealed that over 40 years, open spaces in the Shanghai city center were gradually fragmented and their sizes decreased. Fragmentation of the existing holistic vegetation in open areas and UGSs into smaller pieces in urban areas may cause environmental degradation. This situation is an important threat, especially to the ecosystem, and significantly impacts the protection of biodiversity, environmental quality and urban microclimates [45, 46]. The findings of this study are consistent with previous research on the classification and monitoring of UGS;

however, they advance current understanding by explicitly revealing the relationship between population dynamics and PCGS in the case of Antalya, thereby offering new perspectives for urban sustainability and planning strategies. Furthermore, as emphasized by Manavoğlu and Ortaçesme [30], in UGS areas demonstrating minimal or positive change (Figure 9a, Figure 9d, and Figure 9f), restricting urban development can play a significant role in mitigating UGS losses. In this regard, urban planners and policy-makers may develop protective strategies for such areas to promote the equitable distribution and sustainable management of UGS.

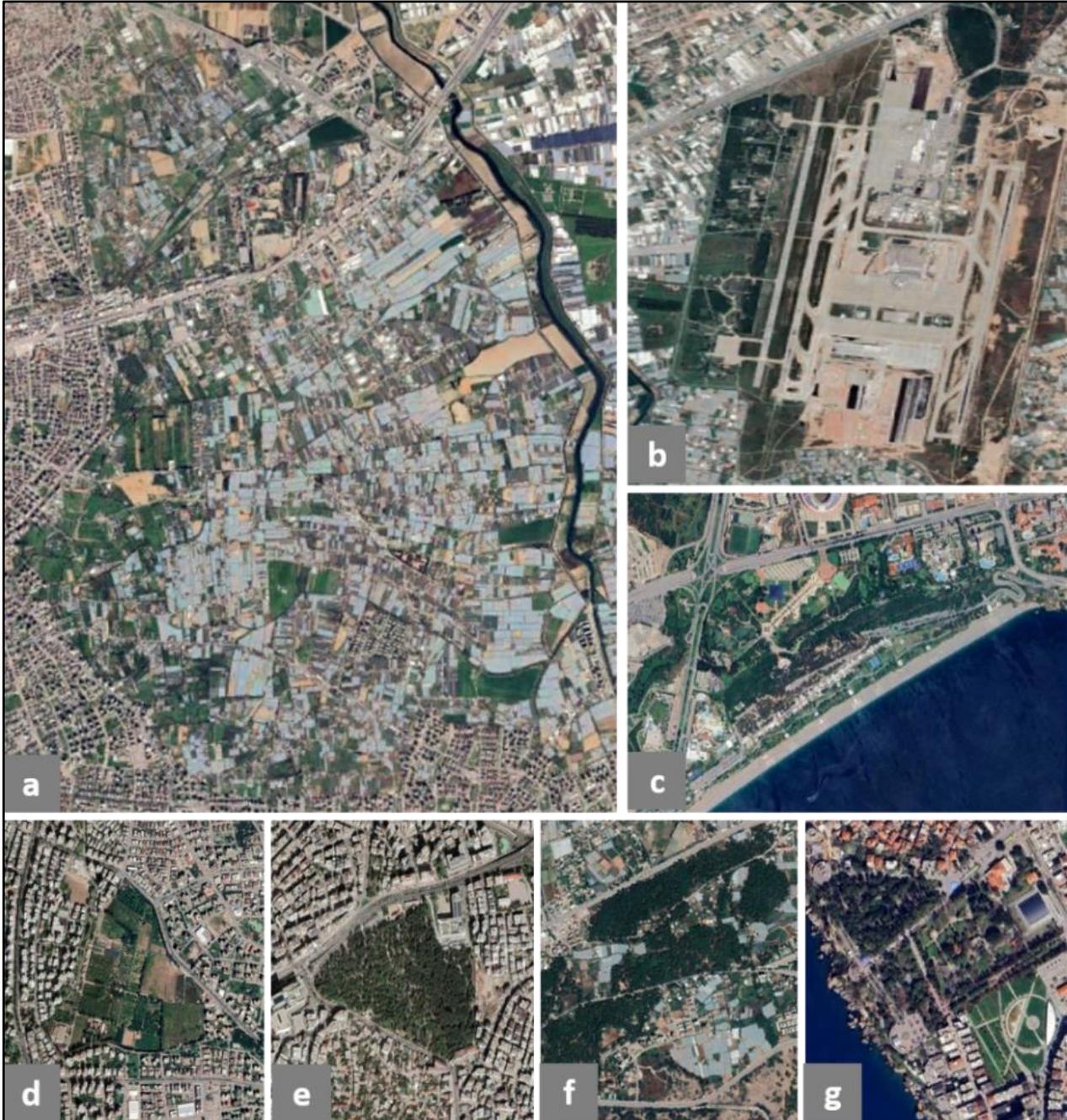


Figure 9. Large UGS sample areas in the study area: (a) Agricultural area, (b) Airport, (c) Park, (d) Agricultural area belonging to a public institution, (e) Urban cemetery, (f) Forest area, (g) Park (Image from Google Earth dated June 2023)

One of the important issues is that not all UGSs have sufficient size and function, as revealed by Pouya and Aghlmand [2]. For example, although Figure 9a, Figure 9b, Figure 9d and Figure 9e, which cover a very large area in Muratpaşa, and contain quite large UGS, these are not areas that the public can use daily. In addition, some UGSs are smaller and inadequate in terms of function since they are in densely populated neighborhoods. In short, as the area covered by UGSs shrinks and the population increases, their functions in these areas decrease. Lockdown and population growth, especially those caused by sudden and rapidly spreading pandemics that may occur on a global scale, such as COVID-19, may also negatively affect UGSs and PCGS [47]. Not UGSs located in Muratpaşa have sufficient size and function, as in Figure 9c and Figure 9g, due to the dense urban texture. As stated by researchers, some UGSs are generally used as children's playgrounds, outdoor fitness equipment areas, walking/jogging tracks, or for recreation. In the planning of UGSs, it is necessary to consider not only quantitative values such as PCGS and impact areas but also the socio-economic, socio-cultural and ecological values of UGSs. In the studies to be carried out in this context, as suggested by Olgun [48], multidisciplinary studies involving professions such as planning, design, engineering and those working in the fields of social sciences, RS and GIS will be more useful.

4. CONCLUSION

This study determined the short-term changes in UGS and PCGS in a dense urban area using Sentinel-2 satellite data, demographic data, and the OBIA method. The OBIA method, which has significant advantages over classical pixel-based classification, was used in the study. The findings obtained from this study are quite high (over 90% OA), as in similar LULC or object detection studies. Additionally, the study utilized UGSI and PCGS values to examine the relationship between urban green space and the city's population across various time points. Analysis results show that there were slight changes in UGSI and PCGS over the short-term from 2017 to 2023, but PCGS (88.68 m² for 2017 and 81.35 m² for 2023) is above the minimum values determined by both Türkiye and WHO (>10 m²), even on a neighborhood basis. This indicates that, despite the city's increasing population and densification trends, the availability of urban green space per capita continues to be relatively sufficient. However, the minor decline observed suggests that future urban development and demographic growth could exert pressure on green space distribution. Therefore, it is crucial for city managers and urban planners to monitor this relationship closely, ensuring that green space planning keeps pace with population growth. Integrating such spatially explicit and temporally comparative analyses into urban planning can contribute to maintaining equitable access to green areas across neighborhoods and safeguarding the ecological and social functions of urban green infrastructure. This study suggests that the findings are transferable to urban areas of varying scales, offering valuable support to managers, urban planners, and landscape architects in promoting more effective and equitable planning practices.

Additionally, it underscores the potential for integrating the remote sensing-based green space monitoring approach into national and municipal green infrastructure planning frameworks, thereby strengthening data-driven decision-making and fostering sustainable urban development. In the future, research will focus on the potential use of the remote sensing-based green space monitoring approach, not only in urban planning but also in precision agriculture, digital agriculture, and smart farming applications, to support data-driven decision-making and sustainable land management.

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REFERENCES

- [1] Li L, Xin X, Zhao J, Yang A, Wu S, Zhang H, et al. Remote sensing monitoring and assessment of global vegetation status and changes during 2016–2020. *Sensors*. 2023;23(20):8452.
- [2] Sun Z, Du W, Jiang H, Weng Q, Guo H, Han Y, et al. Global 10-m impervious surface area mapping: A big earth data based extraction and updating approach. *International Journal of Applied Earth Observation and Geoinformation*. 2022;109:102800.
- [3] Chen G, Zhou Y, Voogt JA, Stokes EC. Remote sensing of diverse urban environments: From the single city to multiple cities. *Remote Sensing of Environment*. 2024;305:114108.
- [4] ESA [Internet]; 2024 [cited 2024 april 25]. Revisit and Coverage. Available from: <https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/revisit-coverage>
- [5] Oke TR. The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society*. 1982;108(455):1–24.
- [6] De Almeida CR, Teodoro AC, Gonçalves A. Study of the urban heat island (UHI) using remote sensing data/techniques: A systematic review. *Environments*. 2021;8(10):105.
- [7] Belal AA, Moghanm FS. Detecting urban growth using remote sensing and GIS techniques in Al Gharbiya governorate, Egypt. *The Egyptian Journal of Remote Sensing and Space Science*. 2011;14(2):73–9.
- [8] Nasser IA, Adam E. Urbanisation in Sub-Saharan Cities and the implications for urban agriculture: Evidence-based remote sensing from Niamey, Niger. *Urban Science*. 2024;8(1):5.
- [9] Chen W, Huang H, Dong J, Zhang Y, Tian Y, Yang Z. Social functional mapping of urban green space using remote sensing and social sensing data. *ISPRS Journal of Photogrammetry and Remote Sensing*. 2018;146:436–52.
- [10] Zhang X, Du S, Wang Q. Integrating bottom-up classification and top-down feedback for improving urban land-cover and functional-zone mapping. *Remote Sensing of Environment*. 2018;212:231–48.

- [11] Anteneh MB, Damte DS, Abate SG, Gedefaw AA. Geospatial assessment of urban green space using multi-criteria decision analysis in Debre Markos City, Ethiopia. *Environmental Systems Research*. 2023;12(1).
- [12] Pouya S, Aghlmand M. Evaluation of urban green space per capita with new remote sensing and geographic information system techniques and the importance of urban green space during the COVID-19 pandemic. *Environmental Monitoring and Assessment*. 2022;194(9).
- [13] Badiu DL, Iojă CI, Pătroescu M, Breuste J, Artmann M, Niță MR, et al. Is urban green space per capita a valuable target to achieve cities' sustainability goals? Romania as a case study. *Ecological Indicators*. 2016;70:53–66.
- [14] Gül A, Dinç G, Akin T, Koçak Aİ. Kentsel açık ve yeşil alanların mevcut yasal durumu ve uygulamadaki sorunlar. *İdealkent*. 2020;11:1281–312.
- [15] Doğu G, Kesim Ü, Sivrikaya Ö. Belediyelerin sporla ilgili işlevleri: Düzce belediyesi örneği. *Çağdaş Yerel Yönetimler*. 2002;11(1):5–14.
- [16] Anonymous [Internet]: 2024 [cited 2024 april 25]. Available from: <https://csb.gov.tr/turkiyede-kisi-basina-dusen-agaclik-yesil-alan-miktari-12-63-metrekare-oldu-bakanlik-faaliyetleri-39952#:~:text=99%20B%C4%B0N%20485%20HEKTAR%20YE%C5%9E%C4%B0L,bin%20331%20dolar%20olarak%20hesapland%C4%B1>
- [17] Neyns R, Canters F. Mapping of urban vegetation with high-resolution remote sensing: A review. *Remote Sensing*. 2022;14(4):1031.
- [18] Sönmez NK, Onur I. Monitoring of land use and land cover changes by using fuzzy supervised classification method: A case study of Antalya, Türkiye. *Journal of Food Agriculture & Environment*. 2012;10(3-4):963–7.
- [19] Soyaslan İ, Hepdeniz K. Coğrafi bilgi sistemleri ve uzaktan algılama kullanılarak Burdur İli arazi kullanımının zamansal değişiminin belirlenmesi. *Mehmet Akif Ersoy Üniversitesi Fen Bilimleri Enstitüsü Dergisi*. 2016;7(2):94-101.
- [20] Deliry SI, Avdan ZY, Avdan U. Extracting urban impervious surfaces from Sentinel-2 and Landsat-8 satellite data for urban planning and environmental management. *Environmental Science and Pollution Research*. 2020;28(6):6572–86.
- [21] Zaki A, Buchori I, Sejati AW, Liu Y. An object-based image analysis in QGIS for image classification and assessment of coastal spatial planning. *The Egyptian Journal of Remote Sensing and Space Science*. 2022;25(2):349–59.
- [22] Yu D, Fang C. Urban remote sensing with spatial big data: A review and renewed perspective of urban studies in recent decades. *Remote Sensing*. 2023;15(5):1307.
- [23] Kucharczyk M, Hay GJ, Ghaffarian S, Hugenholtz CH. Geographic object-based image analysis: A Primer and future directions. *Remote Sensing*. 2020;12(12):2012.
- [24] Moskal LM, Styers DM, Halabisky M. Monitoring urban tree cover using object-based image analysis and public domain remotely sensed data. *Remote Sensing*. 2011;3(10):2243–62.
- [25] Choudhury MAM, Marcheggiani E, Despini F, Costanzini S, Rossi P, Galli A, et al. Urban tree species identification and carbon stock mapping for urban green planning and management. *Forests*. 2020;11(11):1226.
- [26] Popa AM, Onose DA, Sandric IC, Dosiadis EA, Petropoulos GP, Gavriliadis AA, et al. Using GEOBIA and vegetation indices to assess small urban green areas in two climatic regions. *Remote Sensing*. 2022;14(19):4888.
- [27] Simović I, Dubljević JT, Tošković O, Trkulja MV, Živojinović I. Underlying mechanisms of urban green areas' influence on residents' health—A case study from Belgrade, Serbia. *Forests*. 2023;14(4):765.
- [28] Ortaçşme V, Karagüzel O, Atik M, Sayan S. Antalya kentinin aktif yeşil alan varlığı üzerinde bir araştırma. *Akdeniz Üniversitesi Ziraat Fakültesi Dergisi*. 2000;13(1):11-22.
- [29] Manavoğlu E, Ortaçşme V. Konyaaltı kentsel alanında bir yeşil alan sistem önerisi geliştirilmesi. *Konyaaltı kentsel alanında bir yeşil alan sistem önerisi geliştirilmesi*. 2007;20(2):261-271.
- [30] Manavoğlu E, Ortaçşme V. Antalya kenti yeşil alanlarının çok ölçütlü analizi ve planlama stratejilerinin geliştirilmesi. *Akdeniz Üniversitesi Ziraat Fakültesi Dergisi*. 2015;28(1):11-19.
- [31] Muratpaşa Belediyesi [Internet]: 2024 [cited 2024 april 20]. Tanıtım. Available from: <https://muratpasa-bld.gov.tr/icerik/tanitim>
- [32] TSMS. [Internet]: 2024 [cited 2024 april 21]. Antalya. Available from: <https://www.mgm.gov.tr/veridegerlendirme/il-ve-ilceler-istatistik.aspx?m=ANTALYA>
- [33] ESA [Internet]: 2024 [cited 2024 april 20]. Overview. Available from: <https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/overview>
- [34] ESA [Internet]: 2024 [cited 2024 april 20]. Spatial Resolution. Available from: <https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/resolutions/spatial> 20.04.2024
- [35] ESA [Internet]: 2024 [cited 2024 april 20]. Level-2A. Available from: <https://sentinels.copernicus.eu/web/sentinel/user-guides/sentinel-2-msi/product-types/level-2a>
- [36] Hashim H, Abd Latif Z, Adnan NA. (2019). Urban vegetation classification with NDVI threshold value method with very high resolution (VHR) Pleiades imagery. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. 2019;42:237-240.
- [37] Tempa K, Ilunga M, Agarwal A, Tashi N. Utilizing Sentinel-2 satellite imagery for LULC and NDVI change dynamics for Gelephu, Bhutan. *Applied Sciences*. 2024;14(4):1578.
- [38] Aryal J, Sitaula C, Aryal S. NDVI threshold-based urban green space mapping from Sentinel-2A at the local governmental area (LGA) level of Victoria, Australia. *Land*. 2022;11(3):351.

- [39] Rouse JW, Haas RH, Schell JA, Deering DW. Monitoring vegetation systems in the Great Plains with ERTS. In: Third Earth Resources Technology Satellite-1 Symposium; 1973 Dec 10–14; Washington, DC. Washington (DC): NASA; p. 309–17.
- [40] Shekhar S, Aryal J. Role of geospatial technology in understanding urban green space of Kalaburagi city for sustainable planning. *Urban Forestry & Urban Greening*. 2019;46:126450.
- [41] Johnson B, Jozdani S. Identifying generalizable image segmentation parameters for urban land cover mapping through meta-analysis and regression tree modeling. *Remote Sensing*. 2018;10(1):73.
- [42] Kotaridis I, Lazaridou M. Object-based image analysis of different spatial resolution satellite imageries in urban and suburban environment. *Int Arch Photogramm Remote Sens Spatial Inf Sci*. 2020;XLIII-B3:105–12.
- [43] Kuang W, Dou Y. Investigating the patterns and dynamics of urban green space in China's 70 major cities using satellite remote sensing. *Remote Sensing*. 2020;12(12):1929.
- [44] Zhu Y, Ling GHT. Spatio-temporal changes and driving forces analysis of urban open spaces in Shanghai between 1980 and 2020: An integrated geospatial approach. *Remote Sensing*. 2024;16(7):1184.
- [45] Atasoy M. Monitoring the urban green spaces and landscape fragmentation using remote sensing: a case study in Osmaniye, Turkey. *Environmental Monitoring and Assessment*. 2018;190(12).
- [46] Kowe P, Mutanga O, Dube T. Advancements in the remote sensing of landscape pattern of urban green spaces and vegetation fragmentation. *International Journal of Remote Sensing*. 2021;42(10):3797–832.
- [47] Dahu BM, Alaboud K, Nowbuth AA, Puckett HM, Scott GJ, Sheets LR. The role of remote sensing and geospatial analysis for understanding COVID-19 population severity: A systematic review. *International Journal of Environmental Research and Public Health*. 2023;20(5):4298.
- [48] Olgun R. Orta ölçekli kentler için kentsel yeşil alan sistem önerisi: Niğde kenti örneği. *Artium*. 2019;7(1):57–69.

Appendices

Appendix A. 2017-2023 populations of the neighborhoods

Appendix B. Neighbourhoods and UGSI

Appendix C. Neighbourhoods and PCGS

Appendix A. 2017-2023 populations of the neighborhoods

ID	Neighbourhood	Population						
		2017	2018	2019	2020	2021	2022	2023
01	Altındağ	8501	8434	8410	8226	8478	8481	8319
02	Bahçelievler	6144	6083	6209	6272	6265	6230	5892
03	Balbey	1056	1029	999	962	1026	1072	992
04	Barbaros	187	187	183	171	159	174	164
05	Bayındır	8806	8616	8796	8719	8870	8853	8612
06	Çağlayan	25376	26280	27282	27586	28543	28768	27732
07	Çaybaşı	7923	8111	8399	8445	8585	9965	8782
08	Cumhuriyet	11401	11172	11314	11410	11383	11641	11420
09	Demircikara	5090	5104	5177	5283	5398	5301	5153
10	Deniz	7189	7021	6983	6952	7031	6981	6730
11	Doğuyaka	4387	4669	4928	5010	5068	5188	5220
12	Dutlubahçe	10732	10708	10979	11115	11230	11344	11296
13	Elmalı	843	868	929	894	931	962	876
14	Ermeneek	6800	6936	7033	7067	7081	7075	7160
15	Etiler	13884	14081	14602	14603	14621	14704	14547
16	Fener	17292	17415	17753	17631	17957	18058	17175
17	Gebzili	6876	7737	8757	9376	9859	10121	10238
18	Gençlik	6662	6568	6578	6508	6444	6360	6014
19	Güvenlik	13333	13246	13454	13517	13617	13816	13804
20	Güzelbağ	4282	4316	4630	4701	4962	4979	4951
21	Güzeloba	31125	32897	35220	34807	37424	39354	37074
22	Güzeloluk	8547	8669	8906	9005	9101	9156	8846
23	Haşimişcan	1544	1542	1543	1574	1550	1483	1463
24	Kılınçarslan	441	463	459	450	447	425	428
25	Kırcami	2748	2782	2755	2769	2719	2731	2835
26	Kışla	3621	3482	3504	3333	3488	3521	3167
27	Kızılanık	17915	18684	20162	20916	21856	22223	22035
28	Kızılsaray	4615	4577	4633	4596	4606	4734	4621
29	Kızıltoprak	21506	22562	23953	24469	25323	25814	25707
30	Konuksever	20597	20620	21211	21412	21268	21407	21237
31	Mehmetçik	1796	1870	1896	1957	2008	2037	2058
32	Meltem	12307	12246	12370	12234	12281	12158	11916
33	Memurevleri	7626	7484	7443	7409	7493	7414	7119
34	Meydankavağı	27632	28280	28908	29373	29583	29692	28558
35	Muratpaşa	12194	12410	12934	12985	12966	12943	12765
36	Sedir	8511	8478	8617	8610	8480	8509	8346
37	Selçuk	129	127	122	115	119	105	87
38	Sinan	7990	7956	8056	8097	8087	8099	7826
39	Şirinyalı	18315	18537	18793	18724	18430	18227	17683
40	Soğuksu	10546	10404	10635	10811	10803	10797	10547
41	Tahılpararı	1937	1971	2038	1940	1988	2131	1999
42	Tarım	1794	1760	1809	1783	1818	1781	1701
43	Topçular	1024	1394	1260	1414	1321	1198	1019
44	Tuzcular	63	63	63	63	63	63	100
45	Üçgen	10729	10386	10454	10242	10286	10062	10002
46	Varlık	10133	10062	10240	10131	9980	9976	9818
47	Yenigöl	1645	1639	1526	1533	1625	1459	1462
48	Yenigün	21918	23167	23822	24066	24843	25045	24557
49	Yeşilbahçe	17647	17235	17153	17091	16836	16546	16124
50	Yeşildere	4846	4950	5280	5389	5529	5556	5705
51	Yeşilova	2892	2807	2871	2886	2915	2946	2855
52	Yıldız	9285	9174	9276	9287	9325	9333	9251
53	Yüksekalan	8583	8844	9124	9166	9231	9341	9112
54	Zerdalilik	7816	7892	8295	8324	8281	8345	8100
55	Zümrütova	1611	1613	1622	1597	1569	1580	1500

Appendix B. Neighbourhoods and UGSI

ID	Neighbourhood	Population		UGSI* (2017)	UGSI* (2023)
		2017	2023		
01	Altındağ	8501	8319	12.76	12.42
02	Bahçelievler	6144	5892	51.67	44.23
03	Balbey	1056	992	39.18	31.92
04	Barbaros	187	164	58.17	31.81
05	Bayındır	8806	8612	33.43	28.89
06	Çağlayan	25376	27732	34.34	37.28
07	Çaybaşı	7923	8782	28.68	23.56
08	Cumhuriyet	11401	11420	16.83	13.13
09	Demircikara	5090	5153	71.20	60.45
10	Deniz	7189	6730	33.95	25.21
11	Doğuyaka	4387	5220	64.38	65.89
12	Dutlubahçe	10732	11296	17.38	14.38
13	Elmalı	843	876	4.80	6.53
14	ErmeneK	6800	7160	59.99	66.26
15	Etiler	13884	14547	18.58	16.82
16	Fener	17292	17175	52.47	47.50
17	Gebizli	6876	10238	23.21	19.34
18	Gençlik	6662	6014	31.12	28.84
19	Güvenlik	13333	13804	18.16	11.84
20	Güzelbağ	4282	4951	52.33	51.31
21	Güzeloba	31125	37074	47.06	52.29
22	Güzeloluk	8547	8846	54.51	54.80
23	Haşımışcan	1544	1463	62.10	54.25
24	Kılınçarslan	441	428	59.20	40.61
25	Kırcami	2748	2835	73.35	67.19
26	Kışla	3621	3167	21.29	19.62
27	Kızılank	17915	22035	38.17	29.63
28	Kızılsaray	4615	4621	15.41	11.30
29	Kızıltoprak	21506	25707	30.24	25.02
30	Konuksever	20597	21237	20.36	16.98
31	Mehmetçik	1796	2058	76.66	74.25
32	Meltem	12307	11916	66.94	58.30
33	Memurevleri	7626	7119	10.09	7.24
34	Meydankavağı	27632	28558	36.27	27.59
35	Muratpaşa	12194	12765	15.99	16.58
36	Sedir	8511	8346	42.53	34.98
37	Selçuk	129	87	59.74	52.53
38	Sinan	7990	7826	19.04	12.56
39	Şirinyalı	18315	17683	59.01	44.56
40	Soğuksu	10546	10547	31.69	23.42
41	Tahılpazarı	1937	1999	10.77	12.17
42	Tarım	1794	1701	72.49	71.23
43	Topçular	1024	1019	55.06	61.34
44	Tuzcular	63	100	27.16	16.05
45	Üçgen	10729	10002	23.47	20.80
46	Varlık	10133	9818	24.25	18.32
47	Yenigöl	1645	1462	51.08	45.78
48	Yenigün	21918	24557	26.88	22.15
49	Yeşilbahçe	17647	16124	56.14	44.07
50	Yeşildere	4846	5705	46.23	29.85
51	Yeşilova	2892	2855	53.75	55.88
52	Yıldız	9285	9251	15.11	12.83
53	Yüksekalan	8583	9112	37.49	33.65
54	Zerdalilik	7816	8100	29.70	23.12
55	Zümrütova	1611	1500	71.77	70.66

*Values are %

Appendix C. Neighbourhoods and PCGS

ID	Neighbourhood	Population		PCGS** 2017	PCGS** 2023
		2017	2023		
01	Altındağ	8501	8319	4.41	4.39
02	Bahçelievler	6144	5892	40.80	36.42
03	Balbey	1056	992	69.98	60.69
04	Barbaros	187	164	245.45	153.05
05	Bayındır	8806	8612	25.64	22.65
06	Çağlayan	25376	27732	36.13	35.90
07	Çaybaşı	7923	8782	18.26	13.54
08	Cumhuriyet	11401	11420	13.13	10.23
09	Demircikara	5090	5153	87.45	73.32
10	Deniz	7189	6730	14.54	11.53
11	Doğuyaka	4387	5220	285.84	245.86
12	Dutlubahçe	10732	11296	7.67	6.03
13	Elmalı	843	876	6.88	9.02
14	Ermek	6800	7160	449.85	471.87
15	Etiler	13884	14547	9.72	8.40
16	Fener	17292	17175	63.34	57.72
17	Gebizli	6876	10238	20.40	11.42
18	Gençlik	6662	6014	21.27	21.83
19	Güvenlik	13333	13804	7.70	4.85
20	Güzelbağ	4282	4951	517.59	438.96
21	Güzeloba	31125	37074	235.65	219.84
22	Güzeloluk	8547	8846	291.06	282.76
23	Haşimişcan	1544	1463	80.96	74.64
24	Kılınçarslan	441	428	203.63	143.93
25	Kırcami	2748	2835	590.03	523.88
26	Kışla	3621	3167	13.01	13.70
27	Kızılank	17915	22035	26.17	16.52
28	Kızılsaray	4615	4621	8.13	5.95
29	Kızıltoprak	21506	25707	20.03	13.87
30	Konuksever	20597	21237	8.84	7.15
31	Mehmetçik	1796	2058	403.01	340.67
32	Meltem	12307	11916	121.21	109.02
33	Memurevleri	7626	7119	2.69	2.06
34	Meydankavağı	27632	28558	21.03	15.48
35	Muratpaşa	12194	12765	7.70	7.63
36	Sedir	8511	8346	29.01	24.32
37	Selçuk	129	87	603.88	787.36
38	Sinan	7990	7826	8.10	5.46
39	Şirinyalı	18315	17683	62.64	48.99
40	Soğuksu	10546	10547	16.43	12.15
41	Tahılpazarı	1937	1999	11.51	12.61
42	Tarım	1794	1701	580.82	601.94
43	Topçular	1024	1019	652.54	730.52
44	Tuzcular	63	100	174.60	65.00
45	Üçgen	10729	10002	9.65	9.17
46	Varlık	10133	9818	13.27	10.35
47	Yenigöl	1645	1462	5402.25	5448.43
48	Yenigün	21918	24557	12.45	9.15
49	Yeşilbahçe	17647	16124	41.16	35.36
50	Yeşildere	4846	5705	49.28	27.03
51	Yeşilova	2892	2855	631.60	665.15
52	Yıldız	9285	9251	6.44	5.49
53	Yüksekalan	8583	9112	24.75	20.92
54	Zerdalilik	7816	8100	15.60	11.72
55	Zümrütova	1611	1500	562.26	594.73

**/values are m²