Spatiotemporal Evolution Characteristics of Urban Green Spaces in Beijing during the Period of 2013 to 2023: A Remote Sensing Based Analysis

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Abstract: Urban Green Spaces (UGS) can not only provide ecological benefits, like reducing the urban heat island effect and maintaining urban biodiversity, but also provide recreational spaces for residents. Although UGS has been researched in various cities, there has been a lack of specific research on spatial-temporal evolution of UGS system in Beijing. Therefore, this study based off Landsat Collection 2 level 2 Surface Reflectance dataset from USGS data center, extracting surface Normalized Difference Vegetation Index (NDVI) data using algorithms on Google Earth Engine (GEE), visualizing and elucidating the spatial-temporal changes in Beijing from 2013 to 2023 employing GIS technology. This research indicates that over past 11 years, both the total area and vegetation density of Beijing's UGS have a increasing trend. The surface spatial distribution exhibits a pattern of expansion from the edge to the city center. To better conserve Beijing's UGS, this study proposes multi-dimensional solutions including strengthening enforcement and supervision mechanisms optimizing strategic guidance and economic incentives, and introducing innovative technologies alongside public participation. The result of this research provides a crucial scientific basis for the conservation of UGS and sustainable urban development in Beijing, while also offering a reference to related studies in other similar regions.

Keywords: Urban Green Space; Spatiotemporal Evolution; Green Space Quality; Urban Planning; Greening Strategy

1. Introduction

Urban Green Space (UGS) referring to open areas in cities involving yards, forests, lawn, agricultural land, etc., is crucial component of urban ecosystem [1,2], providing benefits and essential services that enhance the environmental quality and human well-being [2,3]. UGS significantly contributes to urban ecosystem in reducing urban heat island [4], regulating climate like carbon sequestration as a basis for carbon balance [5,6], and improving air and water quality (Paudel & States, 2023). Spending time in natural environments is associated with better health outcomes [2,7]. Give functions of UGS, understanding the dynamics and the spatial-temporal pattern of UGS is essential for a sustainable urban development.

As the capital of China and one of the fastest growing cities, as well as Beijing has attracted the attention of the world [8]. Beijing's has earliest established UGS system in China since 1994 [8], acting as a typical example of fast-growing cities that establish greenbelts for protecting the environment and providing open space for residents [9,10]. Beijing's Urban Green Spaces has certain similarities with other international UGS in spatial structure, and there are certain circle rules in the construction of regional ecological space [10,11]. Therefore, Beijing's Green Space have certain representativeness in both international and domestic.

GIS technology and accessible large remote sensing dataset provide a new tool in monitoring urban space dynamics [12,13]. Although Beijing has been well researched in different aspects like biodiversity [10], ecosystem service valuation [14], carbon balance [6,15], and vegetation phenology [16], the quantitative analysis for evolution characteristics of UGS in Beijing over the recent decade is lack of attention. Other long-term study indicates that UGS dynamics are influenced by urbanization pressures, social and economic factors, and policy implications, requiring a multi-scale evaluation while single time point and spatial scale analysis is insufficient [17,18,19].

The evolution of UGS in Beijing based off Satellite image from LANDSAT 8 from 2013 to 2023 combined with Geographic Information

System and Remote Sensing. This study utilizes raw data from Satellite image and process to evaluate the intensity and coverage of UGS. Comparing the temporal-spatial green space changes between 2013 to 2023 in different districts and discussed the evolution pattern of study area. By providing a detailed analysis of UGS dynamics in Beijing, this study offers valuable insights for sustainable urban planning and conservation strategies in Beijing and other similar urbanizing regions.

2. Study Area Overview

Beijing located in the northwestern part of the North China Plain, covering a total area of 16410 km2. The overall terrain is high in the northwest and low in the southeast, the feature is illustrated in the Digital Elevation Model (DEM) map in Figure 1. The western, northern and northeastern parts are surrounded by mountains respectively belonging to the Taihang and Yan Mountain ranges while the southeastern part consists mainly of plains. These mountain areas take approximately 62% of the municipal area. Beijing features a typical temperate, semi-humid continental monsoon climate. The predominant vegetation types include warm-temperate deciduous broad-leaved forests and temperate coniferous forests. By the end of 2022, the city’s overall urbanization rate has reached 87.55%, representing an increase of nearly 9% compared to 2003. [10, 16, 20]

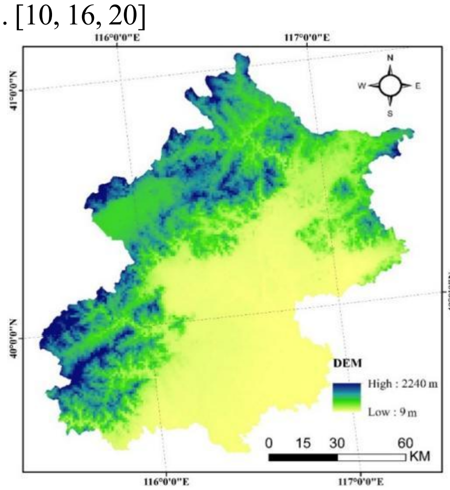

Figure 1. Overview of Beijing Municipality

3. Methodology

3.1 Data

This study employed the Landsat Collection 2 level 2 Surface Reflectance dataset from USGS data center [21], which offers a global coverage and has been processed with atmospheric calibration using Land Surface Reflectance Code (LaSRC) algorithm. By compensating for atmospheric effects like aerosol scattering and thin clouds, this surface reflectance dataset improves the comparability of multi-temporal images within the same region. Additionally, it includes auxiliary data inputs required for calculating the NDVI to bypass the limitations of optical sensor. Annual NDVI raster graphics were calculated by averaging monthly composition from December (last year) to November (Table 1) [21] with known missing data (Table 2) [22] and exported from the GEE after filtering out scene with cloud cover exceeding 10% and processed in ArcGIS. The annual NDVI is a mean composite of all available cloud-free scenes throughout the 12-month period.

Table 1. Dates of Data Acquisition

Data Acquisition Year(s)	Image Composition Period
2013	2013-04* ~ 2013-11
2014	2013-12 ~ 2014-11
2015	2014-12 ~ 2015-11
2016	2015-12 ~ 2016-11
2017	2016-12 ~ 2017-11
2018	2017-12 ~ 2018-11
2019	2018-12 ~ 2019-11
2020	2019-12 ~ 2020-11
2021	2020-12 ~ 2021-11
2022	2021-12 ~ 2022-11
2023	2022-12 ~ 2023-11

* Data acquired from Landsat Collection 2 level 2 surface reflectance in Landsat 8 Operational Land Imager (OLI), available from 2013-04.

Table 2. Missing data which Surface Reflectance processing cannot be applied

Dates (DOY)	Reason
2019: 12.20(354) ~ 12.21(355)	No thermal data; satellite safehold
2020: 11.1(306) ~ 11.3(308)	No thermal data; satellite safehold
2020: 11.4(309) ~ 11.8(313)	No thermal data
2020: 11.9(314)	No thermal data - paths 105, 121, 137, 153, 169, 185
2020: 11.12(317) ~ 11.13(318)	No thermal data; satellite safehold
2020: 11.14 (319)	No thermal data - paths 108, 124
2021: 9.23(266) ~ 9.24(267)	Missing auxiliary input data

3.2 Urban Green Space Classification and Accuracy Validation

To classify UGS using NDVI data, this study employed the GEE Code Editer API to filter and process original satellite image of Beijing. The area of interest was defined in the API, centered at geographic coordinates (39.9°N, 116.4°E). All available data for each year in this region were input and scenes over 10% cloud cover were filtered out. Annual NDVI values were calculated based off the normalized difference between Band 5 (NIR) and Band 4 (Red). These annual value were complied into raster graphic [21, 23]. UGS was classified with the standard of Table 3, and statistics on the extent of green space coverage were computed for each year.

Table 3. Urban Greenspace classification

Class	Standard
Non-Greenspace	NDVI < 0.32 *
Greenspace	NDVI ≥ 0.32

* NDVI is calculated in GEE and visualized in ArcGIS Pro in scaling by a factor of 1000.

For accuracy assessment, a set of random sample point was generated within the study area for corresponding years applying stratified random sampling approach. The sample points were allocated proportionally according to Table 4. These points were then manually classified by visually interpreting high-resolution satellite image on GEE, serving as ground truth reference data. The overall accuracy for the study period was calculated with confusion matrix based off the processed NDVI-based classification result and this reference data.

Table 4. Sample point proportion*

Class	Proportion
Mountain areas (northwest)	62%
Plains (southeast)	38%

* The proportion was determined according to the study area overview

4. Result and Discussion

4.1 Accuracy of UGS Extraction

The overall classification accuracy 86.36%, 85.00%, 93.33%, 86.96%, 85.19%, 83.33%, 90.00%, 87.50%, 81.82%, 89.29%, and 85.71%, respectively. The average overall accuracy across the study period was 86.97% (Figure 2). The average mountain area and plains accuracy was 88.14% and 85.05% (Figure 2)

Potential sources of error in the classification in the analysis are mainly from the acquisition of satellite remote sensing data and processing steps. One factor is the utilization of all year-round data to generate annual NDVI statistics which may not fully account for the influence of seasonal variations on vegetation condition and surface reflectance [24]. Furthermore, the algorithms employed in the Landsat Collection 2 Level 2 Surface Reflectance dataset for atmospheric correction can be blurred or wrongly classified in cloud affected area. Also, data acquired by Landsat involves mosaicking distinct image scenes captured in slightly different period and may result in geometric misalignment. If random sample points for validation fall near seams or overlap areas between those scenes, discrepancies can arise comparing with the reference data. [21, 23, 25]

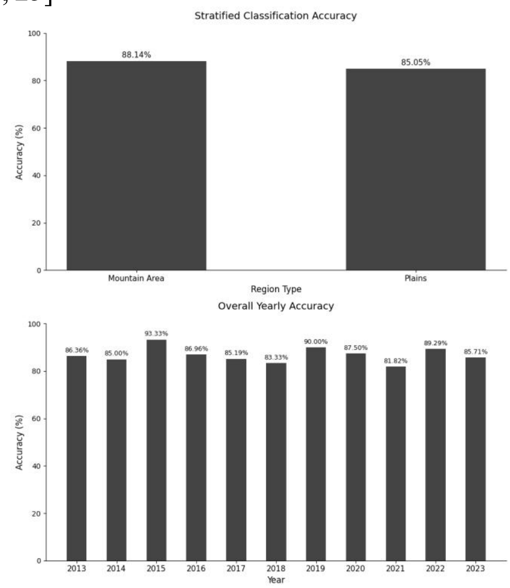

Figure 2. Total Accuracy of Green Space Classification in Beijing from 2013 to 2023

4.2 Trends in Beijing's UGS

The total area of UGS in Beijing is in an increasing trend since 2015. Over the 11 years period, the area increased from 9586.66 km2 in 2013 to 12425.78 km2 with a total increase of 2389.12 km2 (Figure 3). Correspondingly, the proportion of the total urban area classified as UGS rose significantly from 58.42% to 75.72% (Figure 3). Notably, the total UGS was in a sharp increase since 2016. The trend was closely related to urban ecological construction and planning policies implemented by Beijing and its surrounding regions in this period [26, 27], setting long-term goals from ecological conservation and UGS systems, promoting greener techniques for buildings and outdoor spaces.

The average vegetation intensity (represented by mean NDVI value) [28] in Beijing showed a slight increasing trend over the study period. From 2013 to 2023, the mean NDVI value increased by 8.72% related to the 2013 level (Figure 4). The minimum annual mean value during this period was 0.3327 in 2014 and the maximum was 0.3754 in 2023. The increase of vegetation intensity suggests an expansion of UGS area and improvement in the overall health and density of vegetation within Beijing's urban area, reflecting the city's sustained policy efforts in improving air quality, reduce pollution and promoting urban sustainability over the past decade.

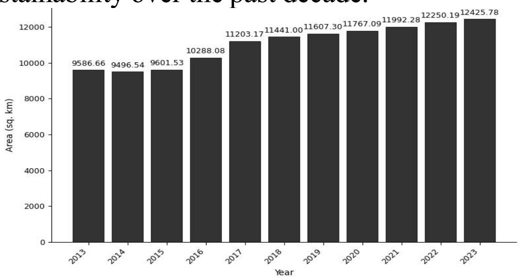

Figure 3. Change in Total Green Space Area in Beijing Municipality from 2013 to 2023

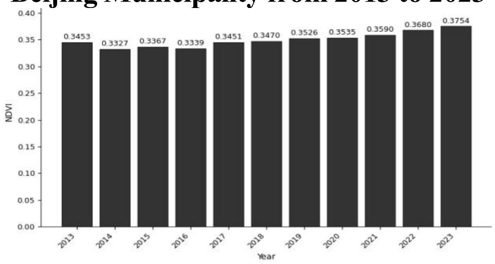

Figure 4. Change in NDVI in Beijing Municipality from 2013 to 2023

4.3 Spatiotemporal Evolution of Beijing's UGS Pattern

The spatial-temporal evolution of UGS distribution in Beijing from 2013 to 2023 is illustrated in the annual classification maps (Figure 5). Visual analysis reveals patterns of change and distinct phases over the study period: Initial Stability, Expansion, Southeastern Growth and Central Intensification.

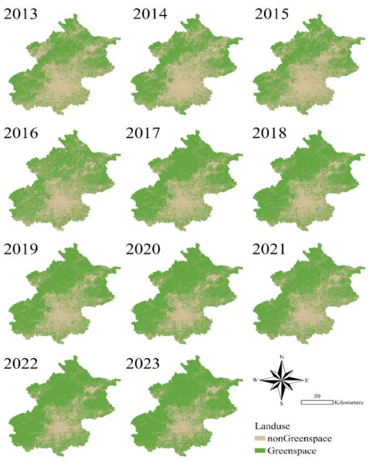

Figure 5. Change in NDVI in Beijing Municipality from 2013 to 2023

In the initial year from 2013 to 2015, the overall distribution of UGS mainly concentrated in the northern and western mountain edge, showing no significant changes. Vegetation intensity has slight variation during this period.

Around 2016, a period of marked change was observed, showing a significant change in green space area, particularly expanding inward from the northern districts towards the central urban core region. Some expansion also occurred in the southern districts. High level of vegetation intensity maintained in the northern edge like northeastern Shunyi and northwestern Changping districts with intensity increase comparing to the previous period and green area visibly expand southwards with a increase of around 6% in area. The overall vegetation intensity in the central urban area also slightly increased with 4.7% in NDVI value, spreading from northern forest area towards south. There were more localized increases in this period. Green space coverage significantly increases in Chaoyang district near Shunyi, and around the Daning Reservoir in southwestern Fengtai district, and also in parts of Haidian district near Shijingshan district with 15% in area.

From 2020, notable changes occurred in the southeastern district and the central core. Green space area significantly increased in southeastern Tongzhou and Daxing district with expansion towards the central city. In the southwestern Fengtai district, the green space development is experiencing a rapid expansion compared to the earlier period with an increase of 17% in area, transitioning from sparse coverage to high intensity green space, radiating outward from Daning Reservoir. Meanwhile, affected by the inward expansion of green space from the northern and eastern edge, the central core experienced a significant increase in overall greenspace coverage and intensity especially in Haidian and Chaoyang districts with 6% increase.

4.4 Analysis and Countermeasures for Beijing's UGS Protection

In recent years, Beijing Municipality has formulated a series of policies and regulations concerning about UGS protection [29] as mentioned in 4.2 [26, 27], providing a legal basis for the protection and sustainable utilization of UGS, stating specific rules regarding urban planning, construction, supervision and management. However, due to the problems encountered during actual implementation, the appearance of destroying UGS still occurs [30]. Due to imperfect enforcement mechanisms and weak accountability for destructive activities, illegal damaging of UGS still remains at a low cost and failing to establish an effective deterrence. Meanwhile, reports from citizens often do not receive seasonable feedback at a lack of mature public supervision mechanisms. Future efforts should focus on coordination between enforcement agencies, clearly defining responsibility entities for UGS protection, increasing penalty levels for destructive activities and establishing platform for public supervision participation to enhance social oversight.

UGS provide not only ecological benefits but also recreational spaces for residents. However, with accelerating urbanization process, conflicts exist between the need for UGS protection and sustainable development and the demand for land resources driven by economic development [31]. Encroachment on UGS due to urban development and industrialization is common and the potential revenue from commercial land use lay pressure on some UGS [32]. The long-term and ecological benefits that difficult to quantify of UGS protection are likely to be ignored in favor of short-term revenue from development. Moreover, the shortage of land resources in central core urban areas aggravates the conflict between UGS conservation and economic development. Future urban planning should aim to enhance the economic value of UGS by developing eco-tourism and green industries. Meanwhile, tax and fiscal policies related to UGS protection can be optimized to provide tax incentives and financial subsidies for green infrastructure construction and conservation projects, encouraging broader social participation, strenthing planning and layout of UGS system and limiting encroachment activities strictly.

With rapid urbanization process, monitoring the dynamic changes in green space is particularly important for urban planning and management [33]. However, current traditional method like manual patrols and reporting are inefficient to capture dynamic changes. Additionally, the utilize of tools like drones and remote sensing lacks integration, result in deficiencies in spatial accuracy, coverage and analytical depth. Therefore, future monitoring should introduce “3S” technologies (Remote Sensing, GIS, GPS) to improve the spatial accuracy and coverage of realtime monitoring [33]. AI techniques including machine learning should also be applied to automatically extract feature and patterns of UGS evolution, differentiate the dynamics of different green space types, and establishing predictive models based off historical data to provide decision supports for conservation [34]. Furthermore, realtime monitoring data should be accessible to the public and research institutions to encourage social participation in UGS protection and feedback.

4.5 Limitations and Outlook

The study covers the period from 2013 to 2023, a total of 11 years. While this allows the analysis of spatial-temporal trends in Beijing UGS evolution during the specific period, it is still limited by its relatively short duration. The evolution of UGS is usually a long-term process influencing by factors like urban planning, ecological environment development and climate change, showing more distinct pattern over longer time scales [35]. Future related research could expand the time scale to cover more extended period of UGS evolution to more comprehensively representing long-term trends and features. Furthermore, the data acquisition period covering all 12 months to maximize data availability across the year instead of the peak growing season, representing annual average conditions rather than peak greenness, which may underestimate the absolute values. The magnitude of increasing trend might be conservative or influenced by non-growing season data. This study's spatial pattern analysis relies on visual interpretation and zonal statistics, which, while effective, do not capture complex morphological characteristics of the green space patches. Future research should employ landscape pattern indices to quantitatively validate patterns and provide a more detailed characterization of landscape fragmentation and aggregation over time.

Also, this study focused only on analyzing the spatial-temporal characteristics of Beijing’s UGS, lacking a quantitative analysis of key driving factors. The specific role of different factors played in driving UGS evolution have not been fully discovered. Future research could employ statistic models and machine learnings to quantitatively analyze the influence of various factors like policy implementation, land use change and climate change. Allowing for an deeper exploration of the relationships between dynamic changes in UGS with driving factors, providing powerful tools to reveal complex driving mechanisms and precisely quantify the interactions between different factors in urban scale.

5. Conclusion

This study based off Landsat Collection 2 level 2 Surface Reflectance dataset from the United States Geological Survey Data Center, extracting surface Normalized Difference Vegetation Index data using algorithms on Google Earth Engine, visualizing and elucidating the spatial-temporal changes in Beijing from 2013 to 2023 employing GIS technology. This research indicates that over past 11 years, both the total area and vegetation density of Beijing's UGS have a increasing trend. The surface spatial distribution exhibits a pattern of expansion from the edge to the city center. To better conserve Beijing's UGS, this study proposes multi-dimensional solutions including strengthening enforcement and supervision mechanisms optimizing policy guidance and economic incentives, and introducing innovative technologies alongside public participation. The result of this research provides a crucial scientific basis for the conservation of UGS and sustainable urban development in Beijing, while also offering a reference to related studies in other similar regions.

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