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Monitoring urban green space for climate-resilient development in the face of rapid urbanization: A tale of two Vietnamese cities

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A R T I C L E I N F O

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A B S T R A C T

Urban green space (UGS) contributes to sustainable and climate-resilient urban development by providing ecosystem services and enhancing public health. In rapidly urbanizing cities, UGS is compromised by expanding built infrastructure, leading to loss and fragmentation of green areas. This study employs a resource-efficient remote sensing approach for monitoring UGS dynamics in two examples of rapid urbanization, Hanoi and Ho Chi Minh City (HCMC) in Vietnam. The approach identifies UGS by applying a ground-truthed threshold to Normalized Difference Vegetation Index quartile maps (NDVI–P75) from nine years of open-access Sentinel-2 imagery before blending it with national census data. The results indicate a pronounced spatial heterogeneity in UGS distributions, with low densities in urban cores and greater availability in the peripheral districts of both metropolises. The temporal analysis shows diverging trends: while UGS areas in Hanoi are relatively stable overall but declining per capita due to ongoing urbanization, HCMC experiences a general decline in both UGS indicators. The findings emphasize the urgent need for implementing integrated UGS strategies that account for the diverse socio-economic drivers of UGS loss. By offering a robust and reproducible methodology for monitoring UGS, this research highlights the potential of remote sensing tools to inform urban planning and policy development. This approach is highly transferable to other urban contexts globally, demonstrating an effective and transparent pathway to foster climate-justice and "sustainable cities and communities" in line with the United Nations' Sustainable Development Goal No. 11.

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1. Introduction

Ensuring public access to green spaces is seen as a fundamental element of sustainable urban development as it contributes to a high quality of life in urban areas (Swanwick et al., 2003; Haaland and van den Bosch, 2015; Mensah et al., 2016). This is also reflected in the United Nations Sustainable Development Goal (SDG) No. 11 "Sustainable Cities and Communities" which explicitly calls for ensuring universal access to green spaces until the year 2030 (United Nations, 2024). Urban green space (UGS) typically comprises multiple types of surfaces covered by vegetation like parks, gardens, roadside greens, or trees (Kabisch and Haase, 2013). It provides essential ecosystem services (ESS) in urban environments. Past research has proven the beneficial impact on human health (Kondo et al., 2018; Aram et al., 2019), urban environments and society, offering unique biodiversity and contributing to ecological and social well-being (Lepczyk et al., 2017; Aronson et al., 2017) as well as cultural significance (Ishii et al., 2010; Ko and Son, 2018). UGS counteracts urban heat islands by enhancing evaporation and providing shading, leading to fresh air generation and a local cooling effect (Priya and Senthil, 2021) and contributes to reducing water-related risks by serving as rainwater infiltration and flood retention area (O'Donnell and Thorme, 2020). Thereby UGS helps to adapt to climate change impacts in the future (Aram et al., 2019) and, additionally, to mitigate climate change through carbon sequestration (Sun et al., 2019). The combination of risk reduction and climate change mitigation measures is also known as climate-resilient development (CRD) and explicitly promoted in the latest assessment report of the Intergovernmental Panel on Climate Change (Schipper et al., 2022).

Especially, many cities in the Global South are challenged by high population pressure, facing rapid socio-economic transformations. Although the World Health Organization (WHO) recommends a minimum UGS per capita of 9 m^2 (WHO, 2012), densification processes in the urban cores and the extension of built-up areas in the peri-urban regions challenge the provision of UGS (Haaland and van den Bosch, 2015; Lu et al., 2023; Rehman et al., 2023; Puplampu and Boafo, 2021). This development is particularly evident in Vietnam, specifically its two most populous metropolises: Ha Noi City (Hanoi) in the North and Ho Chi Minh City (HCMC) in the South of the country. Driven by strong economic growth, both metropolitan regions have experienced significant in-migration since the market reforms of the 1980s (known as Doi Moi), resulting in substantial densification and urban sprawl. Vietnam has recognized the importance of UGS since the early 2000s, with a significant milestone being the establishment of the National Standard TCVN 9257:2012 on UGS planning. This standard specifically addresses the provision of green space per person, recommending that special-class urban areas allocate 12–15 m^2 of green space per capita to ensure environmental quality and urban livability. This reflects a growing awareness of the critical role UGS plays and highlights an urgent need for effective tools to monitor UGS development and support targeted interventions for its conservation.

UGS patterns are typically assessed using remote sensing data where spectral vegetation indices derived from multispectral images quantify vegetation cover and health. These indices are often combined with classification approaches such as pixel-based or object-based image analysis (OBIA) for spatial delineation (Shahtahmassebi et al., 2021). Advanced methods integrate LiDAR or SAR data for structural metrics and use machine learning or deep learning models for automated mapping from high-resolution or UAV images (Huang et al., 2024). Among several alternatives (cf. De et al., 2025), the Normalized Difference Vegetation Index (NDVI) remains the most widely used due to its simplicity and interpretability (Shahtahmassebi et al., 2021). Originally proposed by Rouse et al. (1974), NDVI has become a standard indicator of "an area's greenness" (WHO, 2016). For Hanoi and HCMC, most studies have relied on single NDVI snapshots to analyze UGS, including UGS density (Loi and Duong, 2022; Hai and Trang, 2021) and UGS per capita (Han et al., 2018; Hang and Huong, 2023). UGS in both cities has also been analyzed in the context of ESS like heat island mitigation (e.g. Dang et al., 2018; Nguyen, 2022; Nguyen et al., 2023; Do et al., 2024) and rainwater purification (Do et al., 2024). Temporal analyses of UGS development in Hanoi were conducted by Pham and Labbé (2018), Liou et al. (2021), Hoan et al. (2025). Additionally, Loi and Duong (2022) analyzed the accessibility of UGS (in terms of the minimum distance) in Hanoi and Hoang et al. (2019) in HCMC.

Despite a limited number of individual studies on UGS density and impacts in Hanoi and HCMC, there is a notable absence of scientific efforts to systematically evaluate and compare these two major Vietnamese cities regarding their spatial and temporal UGS developments and in consideration of prevailing urbanization trends. However, independently monitoring the evolution of UGS is becoming increasingly critical for ensuring climate-resilient development in rapidly urbanizing regions. This study seeks to address this gap by answering the following research questions and demonstrating a simple and transferable, NDVI-based approach for monitoring UGS:

i) How are UGS density and UGS per capita distributed across Hanoi and HCMC, and which factors cause these spatial patterns?
ii) What are the temporal dynamics and drivers of significant changes in UGS?
iii) What are the potentials and limitations of integrating NDVI percentile maps and census data as a monitoring tool in urban planning to assess UGS?

2. Material and methods

2.1. Study sites

This study evaluates UGS in the urban districts of Hanoi in the North and HCMC in the South of Vietnam (see Fig. 1a). Hanoi, the capital of Vietnam, includes 12 urban districts which, in turn, are divided into 166 wards over 308 km^2 (Fig. 1b). In 2019, it was home to 3.677 million people with a total of up to 8 million inhabitants living in the wider metropolitan region (General Statistics Office, 2020). The second study site, HCMC, consists of 19 urban districts that are further subdivided into 259 wards (see Fig. 1c). In 2019, the urban districts covering 494 km^2 were inhabited by 6.912 million citizens, contributing to a total metropolitan population of around 9 million (General Statistics Office, 2020). Current population growth rates are ca. 3.4 % per year in Hanoi and 2.6 % in HCMC, respectively (UN-DESA - United NationsDepartment of Economic and Social AffairsPopulation Division, 2024).

Hanoi and HCMC represent the two principal economic and urban centers of Vietnam, shaping the country's economic and societal advancement. HCMC contributes one-quarter of the country's GDP. The city's economy is sustained by a dense concentration of multinational corporations, significant rural-to-urban migration, a large services and manufacturing sector, and an expanding real estate market. The dynamic economy exhibits increasing integration with global markets, leading to accelerated urban expansion and densification - a trend that is reflected in the escalation of real estate values and the expansion of infrastructure (Downes et al., 2024a, b).

Hanoi has been experiencing steady economic growth in the last decades, particularly within the manufacturing and real estate sectors, while retaining a more traditional Vietnamese cultural identity. In August 2008, Hanoi significantly extended its urban boundaries through an administrative expansion approved by the National Assembly of Vietnam, merging Ha Tay Province, Me Linh District from Vinh Phuc Province, and four communes from Luong Son District, Hoa Binh Province. This administrative act effectively tripled Hanoi's size, increasing its total area from 921 square kilometers to 3344 square kilometers and its population to approximately 6.2 million (Resolution No. 15/2008/QH12), aiming to address the demands of rapid urbanization and population growth.

Both cities are situated in different climatic zones: Hanoi, located at 21 °N, is characterized by a humid subtropical climate (Cwa) with an average annual temperature of 24.1 °C and a yearly precipitation of 1624.1 mm (NCHMF - National Center for Hydro-Meteorological Forecasting, 2025). HCMC, located about 1000 km south of Hanoi at 10.8 °N, has a tropical climate (Aw) with an annual average temperature of 27.7 °C. Its annual precipitation rate is slightly higher than Hanoi's, reaching 1922 mm. Both cities are at substantial risk due to the frequent occurrence of extreme weather events and a high vulnerability to natural hazards. Heavy rains, storms, flash floods, coastal floods, and river flooding regularly cause loss of lives and economic damage. The ongoing processes of urbanization and climate change are expected to exacerbate these risks and add to the need for sustainable adaptation strategies to climate change (Scheiber et al., 2023, 2024).

2.2. Satellite data processing

To identify and evaluate UGS in Hanoi and HCMC, we calculated and assessed the NDVI using multi-spectral Sentinel-2 satellite data (ESA, 2024). Therefore, we utilized the entire archive of the Harmonized Sentinel-2 dataset (COPERNICUS/S2_SR_HARMONIZED, Level 2A), covering the period from January 2016 to October 2024, through the Google Earth Engine (GEE; Gorelick et al.,

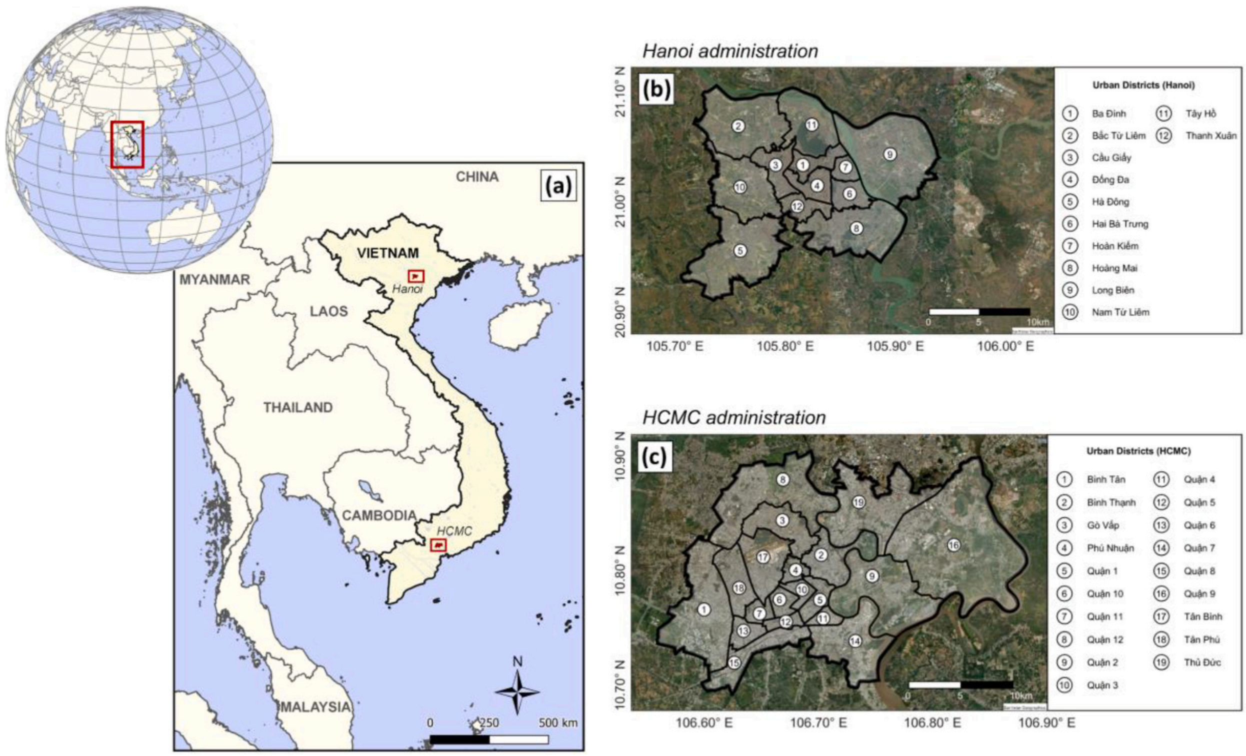

Fig. 1. STUDY SITES. (a) Location of the two study sites in Southeast Asia and Vietnam, respectively. (b) Hanoi in the North of Vietnam including its 12 urban districts. (c) Ho Chi Minh City in the South including its 19 urban districts, where District 2, District 9 and Thu Duc form an individual city-within-city.

2017). NDVI leverages spectral reflectance measurements in the visible red (665 nm) and near-infrared (NIR, 842 nm) bands (Rouse et al., 1974), both of which are available at a 10-m spatial resolution in Sentinel-2 data. NDVI values range from −1 to +1, with negative and low positive values indicating water or areas with little to no vegetation, while higher positive values represent areas with significant vegetation and bioactivity (WHO, 2016). NDVI is computed using the following formula:

$$NDVI = (NIR - Red) \ / \ (NIR + Red).$$

To ensure data quality, we applied a cloud-masking process using the Sentinel-2 Cloud Probability product, which is based on the LightGBM machine learning algorithm (Ke et al., 2017). Pixels with a cloud probability greater than 65 % were excluded. Additionally, edge pixels from the satellite scenes were masked based on valid pixels in the Sentinel-2 bands B8A (near infra-red) and 9 (water vapor) to minimize artifacts. We further calculated the Normalized Difference Water Index (NDWI) on an annual basis to mask out water bodies, which can sometimes be misclassified as vegetation depending on illumination effects. For the remaining valid pixels, we aggregated the NDVI data into annual stacks and computed the 75th percentile (NDVI–P75) for each calendar year (January to December). This was seen as a representative measure of NDVI for both cities, especially because NDVI values reach their yearly minima around December/January at both study sites. The aggregation suppresses low outliers caused by residual clouds, shadows and mixed non-vegetated pixels while still representing the vegetation peak. This robust compositing approach is ensuring a consistent representation of vegetation dynamics and green space development in urban areas over time.

2.3. Data analysis

The applied methodology can be divided into two parts, as visualized in Fig. 2. In the first instance (Fig. 2a), we calculated the UGS densities by setting an NDVI–P75 threshold and then integrating it with ward-specific population data from the most recent national census (General Statistics Office, 2020), resulting in UGS per capita. To obtain the spatial distribution of UGS densities, we generated NDVI maps for 2019, counting each data point with an NDVI value above the predefined threshold as UGS. We counted all UGS cells and divided the sum by the total area of each ward, using its official administrative boundaries, to obtain density values that spatially match the census data. Subsequently, the results were divided by population densities, yielding UGS per capita at ward, district, and city levels.

In the second part (Fig. 2b), we examined the temporal trends in UGS over the observation period. To assess UGS changes over time, NDVI–P75 maps were generated for each year from 2016 to 2024. The resulting 9-year time-series were analyzed for each grid cell using linear regressions, where a positive slope indicates an increase and a negative slope indicates a decrease in NDVI values (i.e., bioactivity), respectively. This regression approach makes the analysis more robust against local, natural, or artificial variability over time.

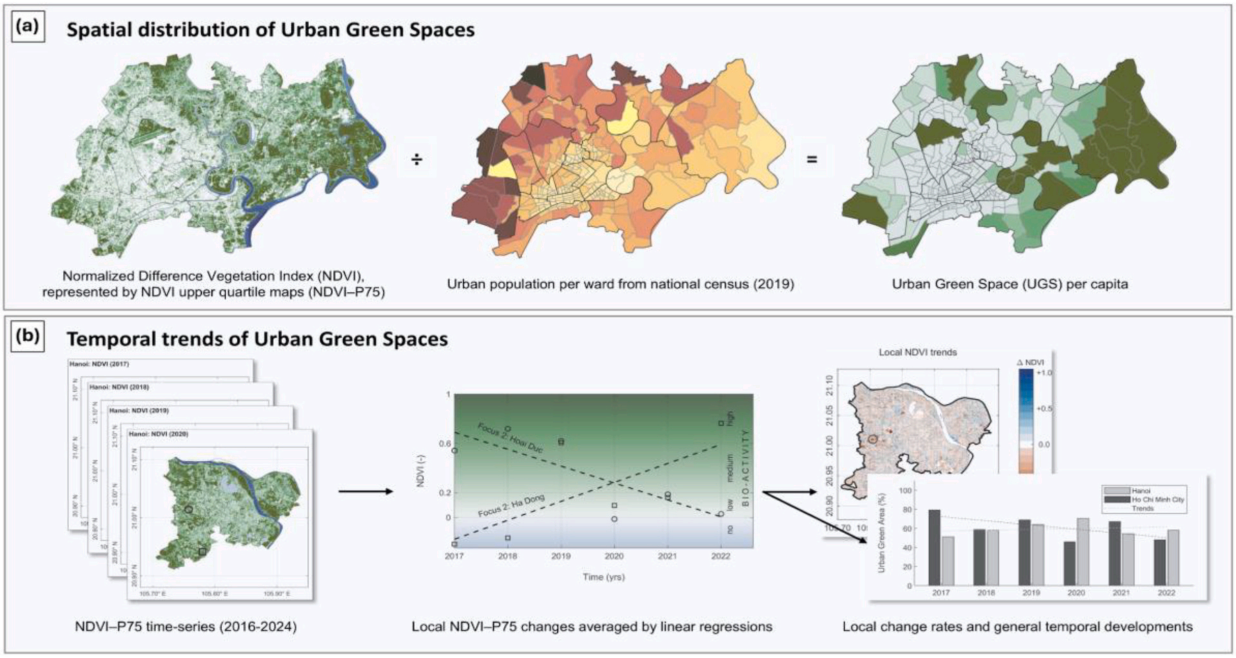

Fig. 2. DATA ANALYSIS. The applied methodology is two-fold: (a) The spatial distribution of UGS is assessed by determining UGS cells with an NDVI above a threshold of 0.4 and dividing these by a layer of population densities from the 2019 national census to yield UGS per capita. (b) The temporal trends of UGS are analyzed by using NDVI time-series to conduct a regression analysis for each grid cell.

3. Results

3.1. Threshold definition

In order to define a reasonable NDVI threshold and be able to classify specific areas as UGS, an initial sensitivity analysis was performed for the NDVI values of selected ground-truthing locations, at which the authors, having local expertise, could ensure that land cover had not changed during the study period. For both Hanoi and HCMC, 15 such ground-truthing locations with a minimum area of 1 ha were selected. Three different types of land cover were analyzed: namely built-up, grassland, and dense vegetation areas. Fig. 3 juxtaposes how the NDVI values developed at these points in Hanoi and HCMC, respectively.

As expected from constant land cover, the NDVI values at these locations do not show distinct temporal trends but rather illustrate the inherent random variability. In general, the three land cover types have very similar value ranges in both cities, with built-up areas characterized by NDVI <0.05, grassland by NDVI ~ 0.5, and dense vegetation by NDVI ~ 0.6. Similarly, the standard deviations within these three land cover classes do not exceed 0.05 with a single exception for grassland in HCMC (SD = 0.08). So, acknowledging that UGS should encompass at least some vegetation (and not just bare soil) to allow for the provision of any ESS, we agreed on NDVI = 0.4 as a suitable threshold to define UGS in our analyses. The limited variability of NDVI values underlines the robustness of this indicator to determine UGS across the two cities.

3.2. Spatial distribution of UGS

The spatial distribution of UGS per capita, derived through a three-step processing workflow, is presented in Fig. 4 in the form of choropleth maps. First, UGS (with NDVI >0.4) is displayed as ward-aggregated relative UGS in square meters per absolute square meter (Fig. 4a). Second, the number of inhabitants and area per ward are combined into a map of population densities in persons per square meter (Fig. 4b). Third, these two layers are divided, yielding UGS per capita in square meters per person (Fig. 4c), which is complemented by a district-aggregated ranking (Fig. 4d).

Both cities show a significant rural-urban gradient with shares of 60 % in the outskirts and peri-urban areas and virtually no UGS in the urban cores. In Hanoi, the lowest values of UGS are observed in the historic center with a gradual increase towards the outer districts that encompass the city core. As Fig. 4a shows, the relative UGS was lowest in *Dong Da* in the city center of Hanoi, with a percentage of 3.5 %, and second lowest in *Thanh Xuan* with 3.9 %. In contrast, the highest percentages are found in the northernmost district *Bac Tu Liem* (43.9 %), and the southernmost district *Ha Dong* (38.5 %), with more than one-third of the area being covered by vegetation. A similar distribution can be seen in HCMC, where UGS is also concentrated in the outskirts and the peri-urban regions. The highest shares of green vegetation are discerned in the newly established city-within-city *Thu Duc* east of the Saigon River, most prominently *District 9* and *District 2* with a relative UGS of 43.3 % and 33.0 %, respectively. The lowest percentage of UGS, in turn, is observed in *District 4* (2.8 %), which is located at the lower meander of the Saigon River, and in *District 6* (3.7 %), marking the urban cores of HCMC. On average, 29.1 % of Hanoi's area and 25.1 % of HCMC were covered by UGS in 2019.

The distribution of population densities (Fig. 4b) exhibits an almost inverse relationship when compared to the patterns of relative UGS. The average population density in Hanoi was approximately 0.0120 persons per square meter (equivalent to 12,000 P/km^2), highlighting the significant concentration of residents within these officially designated urban areas. The highest population density was reported for *Thanh Xuan* and *Dong Da* with 0.0395 and 0.0363 P/m^2, respectively, which also showed the lowest UGS densities. In contrast, the population density in *Long Bien,* located in the Northeast, was the lowest, only amounting to 0.0054 P/m^2. At the same time, the total number of inhabitants in the urban HCMC was 6.912 million at an average population density of 0.0140 P/m^2. The

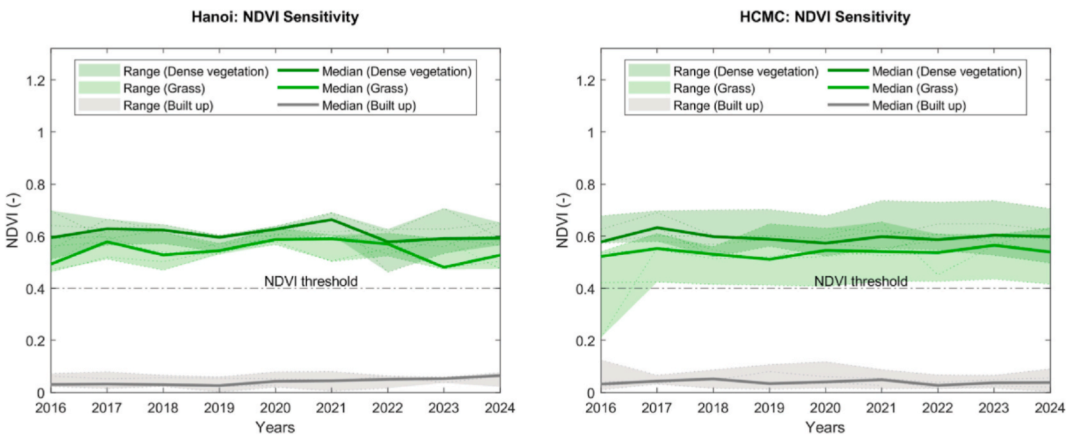

Fig. 3. NDVI SENSITIVITY. For both study sites, Hanoi (left) and HCMC (right), 15 ground-truthing locations were selected known to have sustained one of three pre-defined land cover types during the study period. The illustration shows the temporal variation and median of NDVI values at these locations giving insights into the inherent sensitivity of this index and allowing for the definition of a threshold at 0.4.

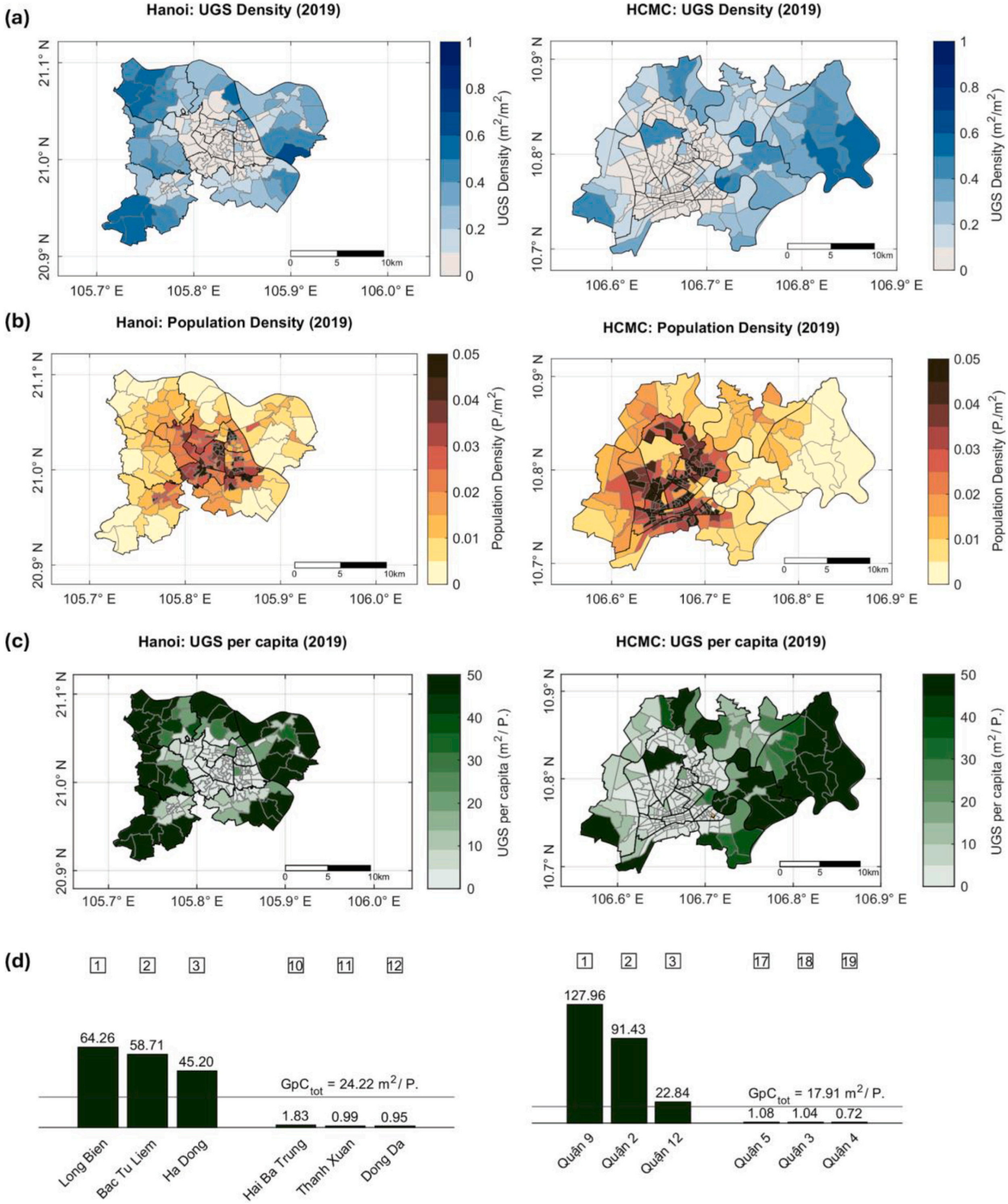

Fig. 4. SPATIAL PATTERNS of UGS. While (a) UGS densities are characterized by the relative area (in m^2/m^2) that exhibits an NDVI >0.4, (b) population densities are defined by the number of persons per square meter (P./m^2). (c) The UGS per capita (in m^2/P.) is the simple ratio of the previous two layers where the ranking in (d) highlights the three highest and lowest district values, respectively.

population density was reported to be highest in the city center, notably in *Districts 10* and *District 11,* both with about 0.040 P/m^2. Consistent with the previously discussed distribution of UGS, the districts east of the historic core exhibited lower population densities. The population density in this area was lowest in *District 9* with ca. 0.0034 P/m^2 and *District 2* with 0.0036 P/m^2, respectively.

The average UGS per capita in Hanoi was 24.22 m^2 per person (Fig. 4c). At 64.26 m^2, the UGS was highest in the easternmost district *Long Bien*, which also had the lowest population density, directly followed by the northern *Bac Tu Liem* with 58.71 m^2, which in turn had the highest UGS density. In contrast, the least UGS per capita was again measured in *Dong Da* and *Thanh Xuan* with only 0.95 m^2 and 0.99 m^2, respectively. These two districts were both leading with respect to high population and low UGS densities. In contrast, the mean UGS per capita in HCMC was 17.91 m^2 and thus about 26 % less than in Hanoi. Examples of high UGS per capita values are especially the new districts east of the Saigon River, namely *District 9* and *District 2,* with 127.96 m^2 and 91.43 m^2, respectively. These were also at the top regarding relative UGS and at the bottom in terms of population density. The lowest UGS per capita, in turn, was calculated for *District 4*, *District 3,* and *District 5* with 0.72 m^2, 1.04 m^2, and 1.08 m^2, respectively, of which District 4 led the previous ranking of relative UGS. The juxtaposition of UGS and population densities underlines how the densification of urban settlements is reciprocally connected to the fate of UGS. UGS per capita at both study sites is highest in the newly integrated peripheral areas of the cities, gradually declining toward the historic urban cores. This pattern reflects a characteristic urban growth dynamic observed up to 2019. For a summary of district-level results, see Table S1 in the Supplementary Material.

3.3. Temporal development of UGS

To understand how UGS in Hanoi and HCMC changed over time, we considered a time-series of nine NDVI–P75 maps, one for each year since 2016, to identify hotspots of change in urban vegetation. Given that the NDVI at a specific location was shown to be subject to at least some variation (cf. section 3.1), we decided to mitigate this effect by applying linear regressions to the time-series of each grid point. Fig. 5 depicts these NDVI trends with increases highlighted in blue and decreases in red color, respectively.

The most significant NDVI decreases in Hanoi are visible in the western district of *Nam Tu Liem*, which also has the highest negative NDVI change rate (ΔNDVI = −0.038 1/a), indicating a systematic degradation of vegetative areas. Although positive change rates could be detected as well, these were far less pronounced relating to the district area and were highest in *Hoan Kiem*, a central district at the right bank of the Hong River, with ΔNDVI = +0.028 1/a. The overall change of NDVI values in Hanoi is slightly positive and amounts to +0.006 1/a. In contrast, the overall NDVI trend in HCMC is negative where values decreased by −0.016 1/a on average.

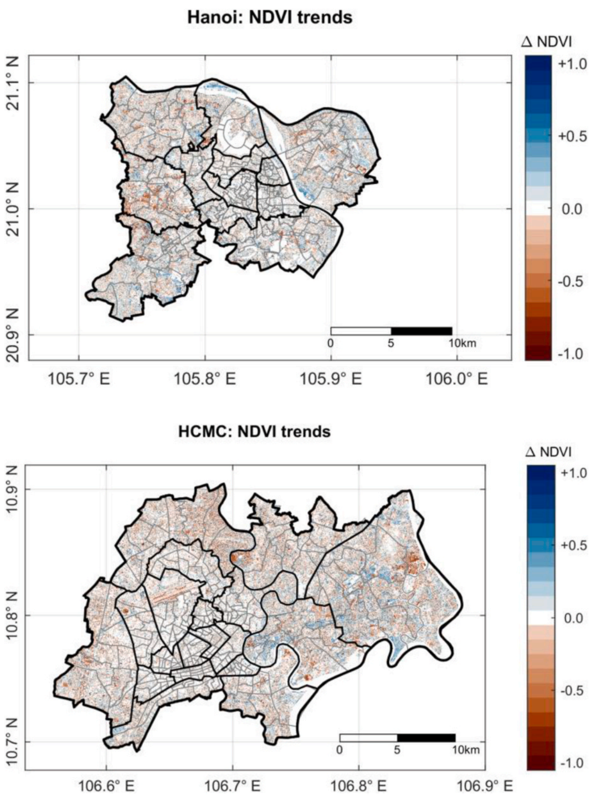

Fig. 5. NDVI TRENDS. Based on linear regressions for each data point, these maps illustrate the overall trend in NDVI values in Hanoi (top) and HCMC (bottom) between 2016 and 2024. The red-to-blue colormaps represent change rates per year and should not be mistaken for absolute differences between start and end dates.

Here, only two out of 19 districts show (slightly) positive NDVI trends with maxima in *District 4* (+0.007 1/a) and *District 2* (+0.003 1/a). However, these uniform changes are far less striking than the local changes that took place in *Thu Duc* and *District 9* because of two large-scale development projects requiring vast amounts of vegetated land to be converted into built-up areas. In fact, many districts in HCMC show negative NDVI trends up to a maximum of $\Delta NDVI = -0.026$ 1/a (*District 12)*. Overall, our monitoring approach tracks significant NDVI changes, and especially decreases, in the peripheral areas of both cities recently undergoing urban development, yet more or less stable values in the established city centers. For a summary of district-level results, see Table S1 in the Supplementary Material.

By applying, once again, the NDVI threshold of 0.4, a deeper understanding can be gained of how the distribution of UGS is developing. While relative UGS in Hanoi was increasing by approximately +0.34 % each year, UGS in HCMC showed a negative change rate of −2.16 %. Combining the resulting annual UGS densities with historic population growth rates at each study site reported by UN-DESA's world population data base then yielded the temporal development of UGS per capita. The population growth in Hanoi was, with an average increase rate of +3.26 % per year, about one-third higher than in HCMC, with +2.42 %. Consequently, these trends are magnified in the UGS per capita, which changed by −5.20 % per year in Hanoi and −6.55 % in HCMC. Thus, the availability of UGS is currently decreasing for citizens at both study sites, but less rapidly in Hanoi than in HCMC. This is driven by a detrimental combination of sustained population growth and the significant degradation of urban vegetation in HCMC, which is less pronounced in Hanoi due to a slightly positive development of relative UGS.

4. Discussion

4.1. Methodological review

Prior to any interpretation, it is important to note the considerable limitations of the presented methodology. Despite utilizing the highest freely available spatial resolution of satellite data (10 × 10 m), the presence of mixed pixels, particularly in heterogeneous urban environments, where vegetation is sparse or mixed with built structures, introduces challenges to accurate classification and may influence the results (Jones and Sirault, 2014; Chen et al., 2018). Although higher-resolution data is available for purchase, the decision was made to use freely accessible data in order to make reproducibility as accessible as possible. It should further be mentioned that the NDVI can be influenced by various external factors such as geographical location, climatic conditions, soil moisture, and the health of the vegetation among others (Yang et al., 2019). An automatic adaptive threshold identification, as proposed for example by Chen et al. (2022), would have restricted the comparison between the two agglomerations.

Another critical restriction is the choice of the considered administrative boundaries, posing challenges when comparing results. In the context of our investigations in Hanoi and HCMC, it has been demonstrated that the UGS densities and, even more so, UGS per capita notably increased towards the outer districts so that a widening of the investigation area, such as the extension of Hanoi's urban boundaries in 2008, inherently leads to higher, i.e. better, UGS results leaving a loophole for political palliation. Additionally, an increase in NDVI values does not automatically equate to an increase in vegetation, requiring that results be interpreted with caution. It has been observed, for example, that the development of construction sites leads to a positive trend in NDVI values, as the roofs of buildings have higher NDVI values than bare soil. Therefore, true-color images and ground truthing should be used for verification, especially regarding the temporal analysis.

Another challenge of the presented approach is the identification of a suitable threshold to distinguish UGS from other intra-urban land covers. We used the 75th percentile as it minimized unwanted effects in the NDVI computation, particularly on bright artificial surfaces such as industrial metal roofs, which were prone to artifacts when using the maximum annual NDVI. Further, the classification of UGS highly depends on the NDVI threshold, which we decided to set at NDVI >0.4 based on the conducted sensitivity analysis. Even

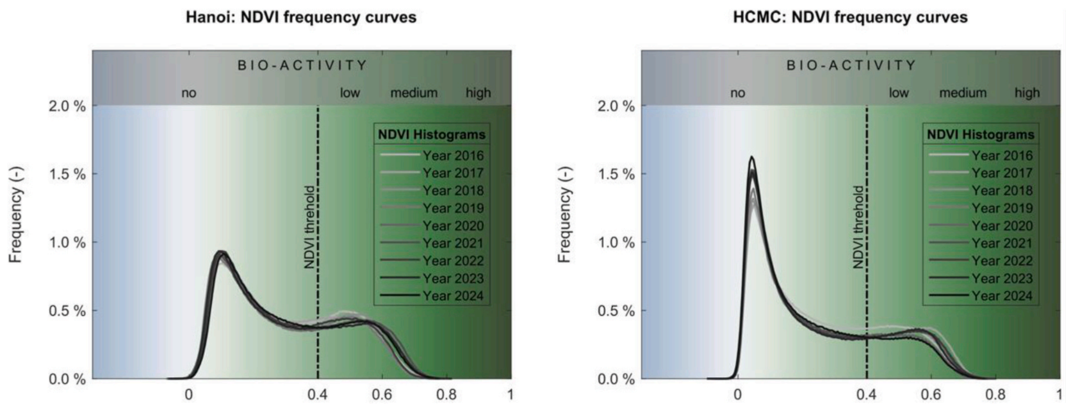

Fig. 6. Normalized NDVI frequency curves for Hanoi (left) and HCMC (right) are characterized by a distinct peak around 0.1, assumed to represent the built-up area in both cities. However, these curves do not show any notable discontinuity that would facilitate a physically founded definition of a vegetation threshold.

though this value was corroborated by insights from multiple ground-truthing locations (cf. section 3.1), it is still debatable whether and which threshold can capture the full range of urban vegetation properly. Fig. 6 illustrates the relative frequency of NDVI values with a distinct peak around 0.13 and 0.10 in Hanoi and HCMC, respectively, representing the most probable NDVI value for built-up areas. As could be expected from the previous analysis of overall UGS density (cf. section 3.2), this peak is higher in HCMC, whereas vegetated areas cover a much larger proportion in Hanoi. It also becomes apparent that the tails of both distributions are continuous and don't show any discontinuities. This underlines that the choice of a threshold somewhere between built-up and sparse vegetation is arbitrary and cannot be physically founded. Accordingly, other publications, which also classified land cover based on an NDVI threshold, have chosen different values (e.g., Aryal et al., 2022). But, notwithstanding the need for a subjective selection of a threshold, which potentially neglects non-typical urban vegetation or bare soil, using a fixed value throughout UGS analyses still allows for a robust comparison of land cover estimates in both space and time.

4.2. Local UGS patterns and drivers

The distributions of UGS and population densities in Hanoi and HCMC show a strong urban-rural gradient in both metropolises, with high concentrations of residents and low availability of UGS in the urban centers. Overall, the most visible differences in observed spatio-temporal UGS trends can be attributed to and seen as a reflection of the distinct socio-economic, political, and urban development dynamics of both cities. HCMC, as Vietnam's economic hub, has experienced rapid urban expansion driven by foreign investment, infrastructure development, and industrial growth, leading to substantial land-use changes, including the large-scale conversion of peri-urban agricultural and vegetated lands into urban developments. Fig. 5 illustrates the transformation of the HCMC urban landscape, driven predominantly by developer-led projects fueled by foreign and private investment. HCMC's outward growth has been accompanied by the development of new urban districts with larger plots of land available for development. Hotspots of development seen are *Van Phuc City*, a 198-ha development by its namesake construction group, located in *District 12* along the Saigon River. Additionally, large-scale construction activities such as the *Vinhomes Grand Park* (270 ha) in *District 9* are visible, alongside recent advancements in the *Thủ Thiêm New Urban Area* in *District 2* and *Celadon City* in the *Tân Phú* district. These developments primarily target high-income residents, catering to the emerging middle class and affluent buyers, marketed with eco-friendliness and smart city concepts. They emphasize modern amenities and engineered green aesthetics but raise significant concerns in regard to genuinely ecological urban planning, and issues of inclusivity, climate gentrification and equitable growth (Hoang et al., 2019; Mabon and Shih, 2021; Shannon, 2024). Despite being marketed as "green townships," these areas often highlight a tension between their marketed environmental values and the socio-economic exclusivity they reinforce (Douglass et al., 2006; Labbé et al., 2020; Downes et al., 2024a,b; Chen et al., 2024). In HCMC's *Binh Chanh* and *District 12*, urban transformation shows a more scattered pattern driven by plot-by-plot development, primarily through self-built housing and informal densification of formerly rural areas (Downes et al., 2024a,b). This approach, spurred by population growth, affordable housing provision, and rural-to-urban migration, has rapidly reshaped these districts. However, the lack of coordinated planning typically strains infrastructure and public services, highlighting the need for more sustainable urban strategies to safeguard UGS (Downes et al., 2016; Thinh and Kamalipour, 2024). In HCMC's *Districts 2* and *9,* which now form part of *Thu Duc City*, the positive NDVI values are suggestive of large construction plots of bare land transitioning back to a vegetative state (scrub and grassland state). This re-vegetation often occurs on land previously cleared for urban or industrial development, which has since stalled due to challenges in financing (fluctuating real estate markets and inconsistent investment inflows) or delays in project implementation. Such areas, characterized by regrowth of vegetation, are a common feature in rapidly urbanizing regions where speculative land clearing typically precedes actual construction by many years. The premature clearing of land in the absence of secured investments or clearly defined development timelines underscores, however, significant uncertainties and inefficiencies inherent in the urban development process of *Thu Duc City* (Harms, 2011, 2020; Huynh, 2015).

In contrast, Hanoi's urbanization has been steadier but more constrained by its dual role as the political capital and cultural heart of Vietnam (Pham and Labbé, 2018; Fuhrmann & Kurfürst, 2023; Thinh et al., 2023). The city's focus on preserving its historical and cultural identity has often conflicted with the need for expansive urban development. Consequently, the central districts of Hanoi have seen a more significant decline in UGS as increasing population pressures have resulted in densification without sufficient UGS integration (Coe, 2015). One example of these construction activities in the inner city is the *Starlake Hồ Tây New Town Project* located close to the West Lake. Providing space for commerce, business, and housing for the high-income classes of Hanoi, a fully urbanized quarter is developed covering a total of 187 ha. The first construction phase, starting in 2010, included the clearance of land and the construction of residential and commercial buildings, leading to a significant decrease in NDVI values visible in Fig. 5. The development of large-scale residential and commercial projects in the *Nam Tu Liem* district in the west of Hanoi is also reflected in a decreasing NDVI trend. With the development of the city metro line and the construction of the ring road no. 3 connecting *Nam Tu Liem* to the inner center, the district is increasingly urbanized. Developer-led projects like the *Vinhomes Smart City, Skylake* or *West Point Projects* are transforming formerly vegetated lands into high-density housing and commercial complexes. *Vinhomes Smart City*, for instance, is a major urban development in *Tay Mo* and *Dai Mo* wards of *Nam Tu Liem* district, encompassing a total area of 280 ha. While they may include small recreational green spaces (e.g., tree-lined streets, urban parks), the net loss of vegetation outweighs these additions, driving the observed NDVI decline.

Comparing the development of Urban Green Space availability in the two metropolises reveals distinct planning paradigms that shape their respective trajectories toward climate-resilient urban growth. HCMC's governance, while centralized, has been more responsive to market-driven approaches, allowing for greater private sector involvement in urban development projects that incorporate UGS as a part of modern urban designs. In contrast, Hanoi's past planning processes tend to emphasize preserving traditional landscapes and adhering (more strictly) to national standards.

4.3. Wider implications

The presented assessment showcases how a simple index like the NDVI, in combination with official census data, can be used to highlight, interpret, and monitor the spatial availability of green spaces in urban contexts and, more importantly, uncover corresponding trajectories. By utilizing NDVI quartile maps, this study advances beyond traditional, mean-based approaches, because NDVI-P75 maps reduce the influence of short-term variability providing a more stable representation of local UGS over time. Even though a quantitative comparison between the two cities may be constrained by several limitations (cf. Section 4.1), the idea of combining UGS estimates, derived through a fixed and site-specific NDVI threshold, with official census data enables valuable per capita assessments. This integration of biophysical and socio-economic indicators is particularly relevant and readily transferable to other rapidly urbanizing cities, where equitable access to green space is under pressure. The simplicity and robustness of the method ensure that it can be applied by local authorities, non-governmental organizations (NGOs) and independent researchers worldwide without requiring specialized tools or knowledge. In response to recent appeals in the Sustainable Development Goals Report, it should hence be mainstreamed into regular assessments to document any (positive or negative) developments in the availability of UGS (UN, 2024). This would add transparency to spatial planning and enable a multitude of urban stakeholders and citizens to actively participate in the development of just and “sustainable cities and communities” as envisioned in SDG No. 11.

The promotion of public UGS is furthermore important because of its potential in fostering climate-resilient urban development. More effectively than any other urban land-cover type, UGS contributes to both the mitigation of climate change (due to carbon sequestration) and adaptation to negative climate-related impacts (e.g., due to infiltration of precipitation and mitigation of heat stress by evapotranspiration). In combination with benefits for ecosystems and corresponding ESS (e.g., on human well-being), UGS is an essential element to improve urban habitability and ensure future-proof living conditions in cities. In scrutinizing the per capita availability of UGS and uncovering its decrease in Hanoi and HCMC, this study not only proposes a cost-effective, transparent, and scalable monitoring framework but also highlights the urgent need for a shift in spatial planning paradigms in these two poles of Vietnam. In Hanoi and HCMC, implementation will require different approaches depending on the prevailing urban structures, for instance the greening of roofs and façades in the highly densified centers or the preservation and expansion of existing parks in the outskirts. In either case, the consideration of UGS in future urban planning will doubtlessly be of low regret and contribute to the climate resilience of the two example cities and other metropolitan regions beyond Vietnam.

5. Conclusion

UGS is vital for providing ESS, improving public health, and enhancing urban livability. The potential for mitigating urban heat, managing heavy rainfall and excessive runoff, and sequestering carbon underscores the importance of UGS in sustainable urban development, specifically towards SDG No. 11. Our analysis identifies significant spatial disparities in UGS distributions, with dense urban centers showing low UGS per capita compared to peripheral areas of both cities. However, while Hanoi exhibits a slight increase in absolute UGS over time, HCMC faces a general decline in UGS per capita due to both shrinking UGS and accelerated urbanization. This highlights the need for careful spatial planning to ensure equitable access to green spaces, considering the heterogeneous urbanization patterns discussed for each city. Utilizing a robust remote sensing approach, including the pre-definition of a ground-truthed threshold and the comparison with NDVI quartile maps (NDVI–P75) from globally available Sentinel-2 imagery, for monitoring UGS offers a readily transferable framework that can be applied to many other urban areas globally. The methodology can aid in independently monitoring and transparently communicating spatial and temporal changes in green infrastructure as a pre-requisite for informed and equitable urban policymaking. In fact, there is an urgent need for integrated urban planning approaches that prioritize UGS conservation and enhancement. Strategies should hence balance urban growth with the preservation of existing UGS to ensure climate-resilient development and improve urban environments. Decision-makers should further consider implementing diverse urban greening strategies, such as the greening of roofs and façades in densely populated areas and the expansion of parks in urban peripheries. The findings highlight the importance of pro-active urban planning and the need to identify and address challenges posed by urban densification. Continued and transparent monitoring and strategic interventions are crucial to maintain and enhance UGS, ensuring that urban growth is both sustainable and equitable. These conclusions suggest that UGS not only enhances urban quality of life but also provides critical infrastructure for sustainable city development, requiring committed efforts from policymakers and urban planners to address current and future challenges. Besides the improving resolution of free satellite imagery, innovations in remote sensing sensors and machine-learning-based pattern recognition will further enhance the accuracy of UGS detection and facilitate independent research at a higher level. In addition, integrating social indicators could improve the applicability of the results and enhance policy relevance.

CRediT authorship contribution statement

Leon Scheiber: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vera Zühlsdorff:** Writing – review & editing, Methodology, Investigation, Formal analysis. **Duong Huu Nong:** Writing – original draft, Validation, Methodology, Funding acquisition, Data curation. **Thanh Son Ngo:** Writing – original draft, Validation, Investigation, Data curation. **Nigel K. Downes:** Writing – review & editing, Writing – original draft, Validation, Investigation. **Felix Bachofer:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Hong Quan Nguyen:** Writing – review & editing, Validation, Investigation, Data curation. **Matthias Garschagen:** Writing – review & editing, Supervision, Funding acquisition. **Andrea Reimuth:** Writing – review & editing, Writing – original draft, Supervision,

Investigation, Conceptualization.

Ethical statement

- All authors have agreed to submit this manuscript to Remote Sensing Applications: Society and Environment.
- This work is not under consideration for publication elsewhere and will not be submitted elsewhere before a final decision is made.
- The written work is entirely original, and that work and/or words of others has been appropriately cited or quoted.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT (GPT-3.5) by OpenAI Ireland Ltd. to check and make suggestions to improve the readability of single sections, namely abstract and conclusions. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rsase.2025.101820.

Data availability

All data used are freely available as referenced in the text.

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