Identifying Spatiotemporal Characteristics of Carbon Storage in Green Spaces of Newly Developed Residential Areas Using High-resolution Mapping

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Abstract: Urban green spaces (UGSs) play a crucial role in mitigating climate change by offsetting carbon dioxide (CO_2) emissions. Despite their importance, the carbon storage (CS) function and spatiotemporal mapping of residential green spaces have received limited research attention. This study examines three newly developed residential areas in the Budapest Agglomeration. Using very high-resolution orthophotography imagery and stereophotographic vegetation height data, combined with a tree height-carbon storage model, the study mapped the spatiotemporal characteristics of CS in residential green spaces from 2015 to 2022. The findings reveal notable variations in CS across newly developed residential areas over the seven years. It provides landscape planners with valuable theoretical guidance on how to accurately understand, locate and enhance the CS function of residential green spaces. The study also identifies a significant positive correlation between green space percentage changes and CS overall. However, poorly planned increases in green space percentage can adversely affect CS capacity. In the context of global warming, this research presents a high-precision, transferable methodology for spatiotemporal monitoring of CS, which can be adapted to other urban areas. This approach provides a robust framework for supporting sustainable urban development and informing climate change mitigation strategies. In Hungary this study contributes to the introduction of the instrument called "green certificate" which is planned to be the tool that makes green space planning more relevant and efficient.

Keywords: Carbon storage change, vegetation height, green space percentage change, high-resolution mapping, landscape design supporting.

1 Introduction

The climate crisis, exemplified by global warming, has emerged as one of the most pressing global environmental challenges, primarily driven by accelerated emissions of greenhouse gases such as carbon dioxide (CO_2) (HOBBIE & GRIMM 2020). In the summer of 2022, the European Union (EU) experienced its highest recorded temperatures, with Eastern EU particularly affected by significantly higher-than-average temperatures in August (COPERNICUS 2022). To mitigate climate change, the 2016 Paris Agreement called for nations worldwide to reduce greenhouse gas emissions and enhance carbon sinks to slow global warming. Against this backdrop, the EU has committed to achieving carbon neutrality by 2050 (CAPROS et al. 2019). As urban areas host over half of the global population and account for approximately 75% of total CO_2 emissions, cities play a critical role in climate change mitigation and in supporting the EU's carbon neutrality goals (GRIMM et al. 2008).

UGSs are integral components of urban ecosystems, contributing to CS through photosynthesis and other ecological processes (NOWAK et al. 2013). Investigating the carbon storage

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services provided by UGSs is essential for understanding the global carbon cycle and guiding sustainable urban development (MITCHELL et al. 2018). In recent years, scholars have undertaken measurements of the CS of UGSs in the EU. For instance, Luca Rossi assessed CS in urban trees in Perugia, Italy (ROSSI et al. 2022), while Zbigniew Szkop quantified CS across 41 UGSs in Warsaw, Poland (SZKOP 2022). Similarly, Márton Kiss examined the CS of park trees in Szeged, Hungary (KISS et al. 2015). UGSs in other EU cities have also received attention, as demonstrated by comparative research on UGSs in Budapest and Vienna (HASSAN et al. 2024).

The residential areas with private gardens within the land plots play a significant ratio of the UGSs in the agglomeration of Budapest (JOMBACH et al. 2023). However, existing research within the EU primarily focuses on quantifying CS in UGSs and trees, with limited exploration of the spatial and temporal characteristics of CS in residential green spaces. To address this gap, this study examines the CS of green spaces in three recently developed residential areas in Hungary, utilizing a tree height-carbon storage model with high-resolution remote sensing data of stereophotographic image processing method. This study aims to (1) map the spatial distribution of green space carbon storage; (2) document temporal characteristics of carbon storage; and (3) analyse the drivers of carbon storage's spatiotemporal characteristics.

2 Pilot Area, Material and Method

2.1 Pilot Area

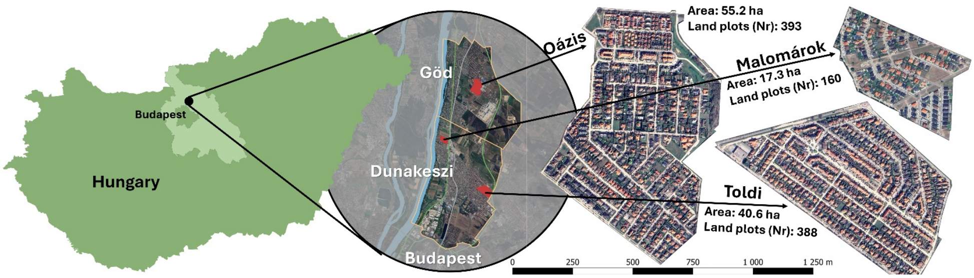

Fig. 1: The location of the three residential area in Budapest Agglomeration (Hungary)

The study sites are three residential areas called Toldi, Oázis, and Malomárok, apartment parks located in the Budapest Agglomeration, Hungary (Fig. 1.) in the towns of Dunakeszi and Göd. The constructions have been started in the first decade of the 21st century only within 10 km distance from the capital boundary. The neighborhoods were developing quickly before the economic crisis in 2008 and slowly land plot by land plot after that. The majority of the houses were designed as semidetached houses, twin houses and apartment buildings with minimum green coverage from 25% to 60% required in the local regulation. In the study period between 2015 and 2022 these plots underwent significant changes partly due to new residential construction projects with loss of green space and partly due to growth of green space or vegetation height. Most of the residential sites are advertised as apartment parks with significant green coverage. The former land use was mostly arable land or grassland in each case. As such, these newly developed residential areas serve as ideal pilot sites for monitoring changes in green space carbon storage.

2.2 Material and Method

(1) In the Data Acquisition phase: high-resolution near-infrared orthophotographic imagery (0.4m spatial resolution) was obtained for three newly developed residential areas in the Budapest Agglomeration. This dataset, updated nationwide every 2-3 years, was complemented by vegetation height data extracted from a normalized surface model (0.8m spatial resolution). For this study, data from 2015 and 2022 was used, sourced from the (LECHNER KNOWLEDGE CENTRE 2019) (Fig. 2).

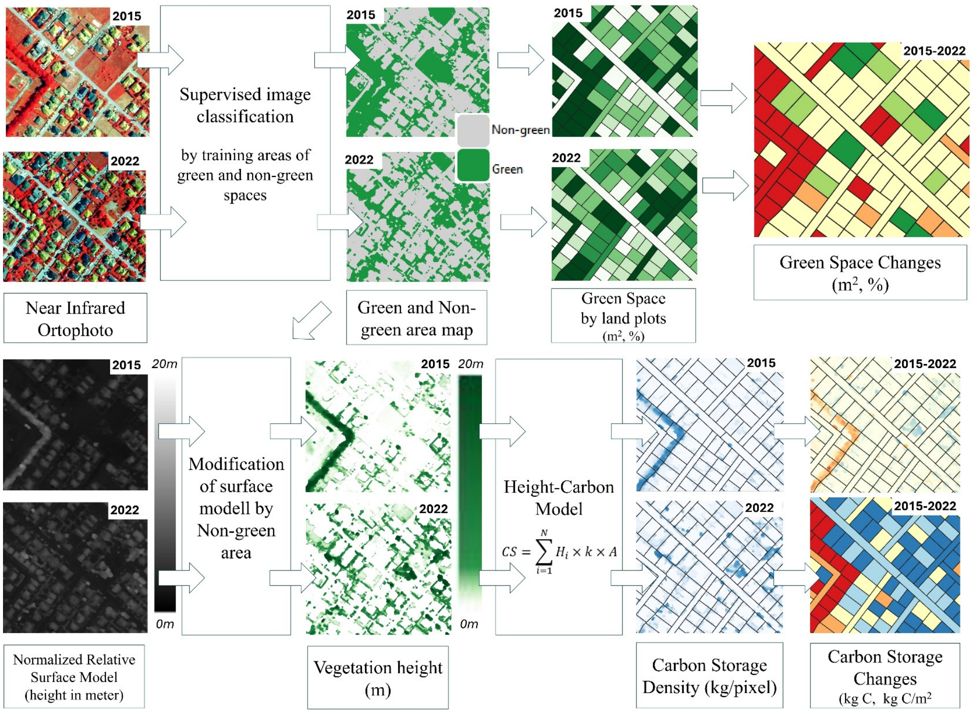

Fig. 2: Methodology framework for assessing carbon storage in residential areas of the Budapest Agglomeration

(2) In the Data Preprocessing phase: supervised image classification was applied to the infrared orthophotography using training samples, categorizing areas into green spaces and non-green spaces (including built-up areas, bare soil, paved surfaces, and water bodies). The relative height surface model was then adjusted by setting all non-vegetated areas to zero using QGIS, ensuring that only vegetation height remained in the model.

(3) In the Carbon Storage Estimation phase: The calculation of CS is based on high-resolution vegetation height imagery and a vegetation height-carbon storage model. This model, developed by Hurtt in 2004 from research on CS in Costa Rican forests, integrates the advantages of LiDAR remote sensing technology and the Ecosystem Demography Model (HURTT et al. 2004). Similar to LiDAR technology, in this research we applied stereophotography-based surface model that provides precise data on vegetation height distribution, which serves as a critical input for CS estimation. The model establishes a statistical relationship between vegetation height and ground-based observations of biomass and CS, enabling the quantification of carbon storage dynamics across different successional stages, such as transitions from early secondary forests to mature forests. Furthermore, the applied model has been originally validated with field measurement data, demonstrating an estimation error of less than 1.2% compared to observed values. Therefore, in this study, the total carbon storage within residential areas is calculated as follows:

$$CS = \sum_{i=1}^{N} H_i \times k \times A$$

where N represents the total number of pixels, H_i is the vegetation height (in meters) of the i -th pixel, k is the carbon storage coefficient (k = 0.26, in kg/m^2) (HURTT et al. 2004), and A is the area of a single pixel (A = 0.16, in m^2 thanks to 40cm geometric resolution). The analysis was further developed to get results in carbon storage density (CSD) in kg C/m^2. The method was extended by classified green spaces with green space coverage calculations in hectare (ha) for all the three sites and in square meters (m^2) for land plots. Additionally, green space percentage (%) was generated for every plot and each site.

3 Results

3.1 Overview of the Carbon Storage in Three Residential Areas

Carbon Storage (CS): In both 2015 and 2022, Oázis had the highest CS, while Malomárok had the lowest. Over this period, all three residential areas experienced an increase in CS, with Oázis showing the largest growth, from 129.6 tons to 170.3 tons (an increase of 40.7 tons). Malomárok, in contrast, had the smallest increase, adding only 6.5 tons of CS.

Carbon Storage Density (CSD): All three areas displayed an upward trend in CSD. Oázis not only had the highest CSD but also the most significant increase, rising from 0.23 kg/m^2 to 0.31 kg/m^2.Unlike total CS, Toldi and Malomárok exhibited very similar carbon storage densities, both starting at 0.10 kg/m^2 in 2015 and differing by just 0.01 kg/m^2 by 2022.

Green Space and Green Space Percentage: Oázis and Malomárok showed a marked decline in both green space area and green space percentage, while Toldi demonstrated an increase in both metrics. Between 2015 and 2022, green space percentages in Oázis and Malomárok fell by 22.93% and 18.62%, respectively. Meanwhile, Toldi's green space area increased by 3.1 hectares, accompanied by a 7.5% rise in green space percentage.

In summary, from 2015 to 2022, Toldi showed a consistent increase in CS, CSD, green space area, and green space percentage. In contrast, Oázis and Malomárok experienced CS and CSD growth despite declines in green space area and percentage This difference stems from

Toldi's early development, where green space expansion dominated, whereas Oázis and Malomárok had multiple plots under construction during the study period (Fig. 3).

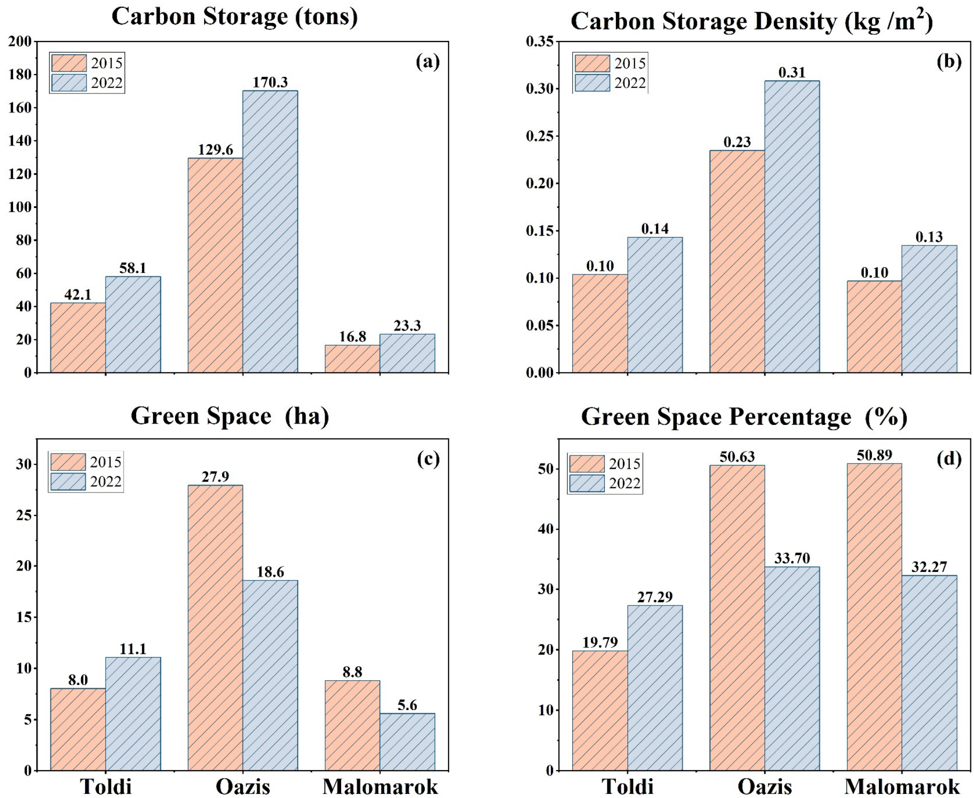

Fig. 3: Overview of Carbon Storage (a), Carbon Storage Density (b), Green Space (c) and Green Space Percentage (d) in Toldi, Oázis and Malomárok from 2015 to 2022

3.2 Carbon Spatiotemporal Characteristics in Three Residential Areas

High CS plots are mainly found in the southwestern and eastern Toldi residential area, where private gardens cluster, while low CS areas are centered around the main square. From 2015 to 2022, CS generally increased, with 72% of plots exhibiting growth. Public roads saw significant CS gains. Meanwhile, several plots declined, mainly in the west and a few in the east. Even in 2022, these declining plots still maintained moderate CS levels (Fig. 4).

The eastern Oázis shows high CS due to dense public greenery, while private gardens in the central area also exhibit relatively high CS. In contrast, the northern, southwestern, and south-eastern parts have lower CS, offering potential for improvement.

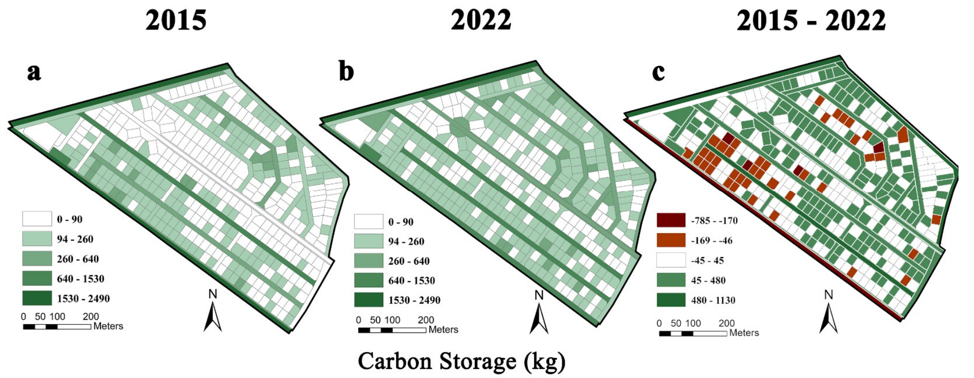

Fig. 4: Spatiotemporal characteristics of carbon storage (a, b, c) (kg) in Toldi residential area

Over seven years, the majority of plots in Oázis have shown an upward trend in CS. Specifically, 53% of plots saw CS growth, with the eastern region benefiting from effective green space management. Meanwhile, CS declined in the southwest, where land cover changed from undeveloped green space (2015) to private gardens with twin houses (2022) (Fig. 5).

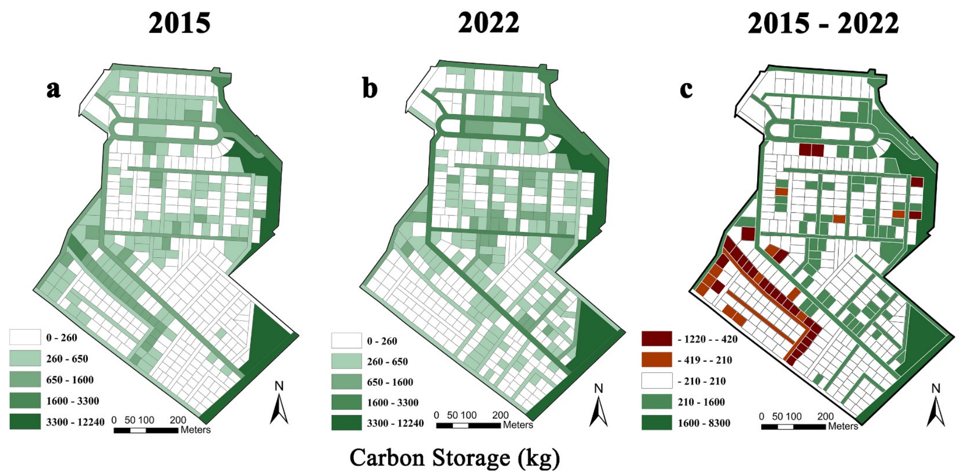

Fig. 5: Spatiotemporal characteristics of carbon storage (a,b,c) (kg) in Oázis residential area

CS levels in Malomárok were higher in the north and lower in the east and southeast. In 2015, high-carbon-storage plots were mainly in the east and along streets, while low-carbon-storage plots clustered in the central and southern areas. By 2022, high-carbon-storage plots shifted to the west and north, while low-carbon-storage plots became concentrated in the east and south (Fig. 6).

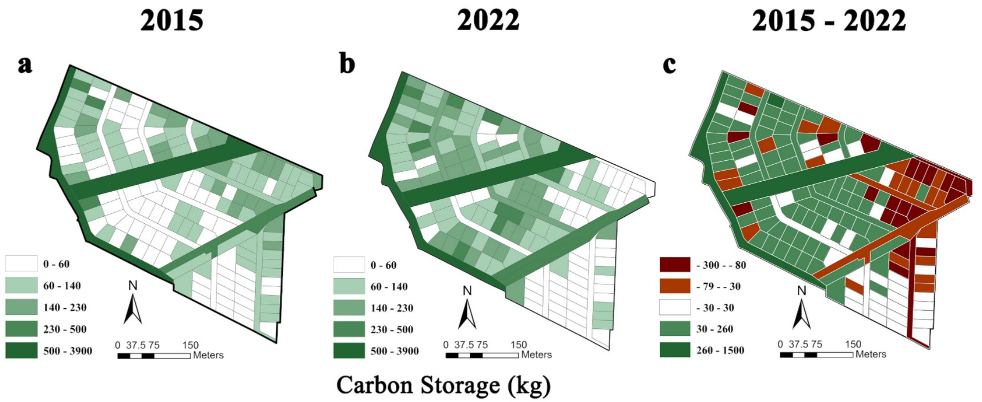

Fig. 6: Spatiotemporal characteristics of carbon storage (a,b,c) (kg) in Malomárok residential area

Between 2015 and 2022, the east and south saw significant carbon storage losses, affecting 61% of the total area (98 plots). In contrast, gains were mainly in the west and center. Extensive land cover changes transformed the area from green space to residential development, leading to notable differences in carbon storage trends, particularly between the east and the central-western regions (Fig. 6).

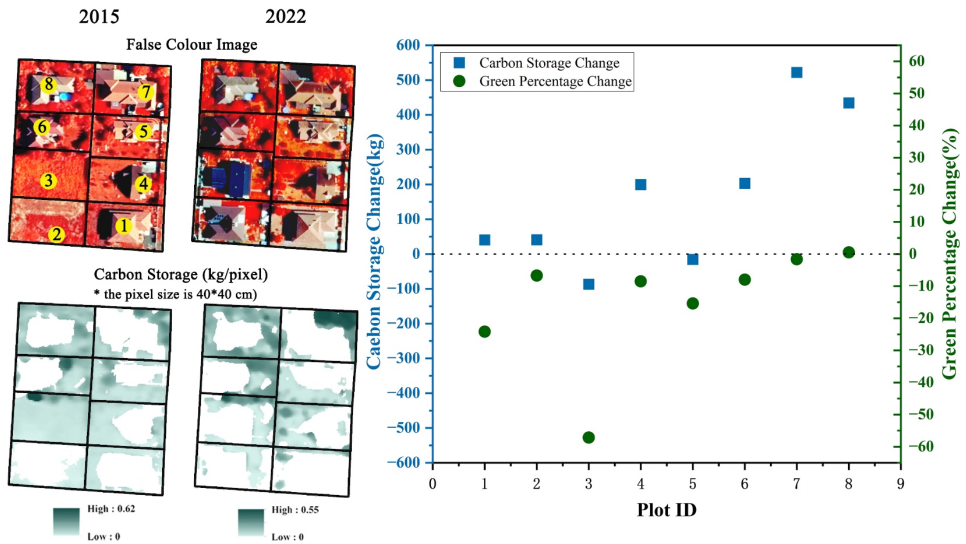

Fig. 7: Carbon storage change and green space percentage in selected plots. Left: False-color image and carbon storage. Right: Carbon storage and green space percentage change.

Eight plots in Oázis were analyzed to assess the relationship between green space percentage and CS (Fig. 7). Despite varying degrees of green space loss from 2015 to 2022, most plots showed CS increases. Plots Nr.7 and Nr.8 had the highest CS growth (522 kg and 434 kg) with minimal green space change, driven by natural vegetation growth. In contrast, plot Nr.3 lost 57% of its green space due to housing construction (2015-2020), leading to an 86 kg CS decline. Among plots with existing buildings in 2015, only plot 5 experienced CS loss, attributed to the removal of two trees west of the house.

In conclusion, the observations from the eight plots reveal a clear response relationship between green space percentage and CS. However, CS exhibits resilience to changes in green space percentage, as moderate reductions in green space percentage do not significantly impact CS.

4 Discussion

The study found that CSD in residential green spaces is lower than in urban areas of Beijing (SUN et al. 2019), comparable to Xi'an (YAO et al. 2015) and significantly lower than in 71 urban parks in South Korea (JO et al. 2023) (Tab. 1).

This disparity can largely be attributed to differences in green space planning and usage. Studies in Beijing and Xi'an focus on public green spaces across the entire city, not just community green spaces. In recent years, China's growing emphasis on urban ecological development has enhanced the ecological functions of these public green spaces. In contrast, private gardens in Budapest's residential areas lack a unified focus on ecological functionality. Specifically, urban green spaces in China achieve higher CSD through comprehensive green space planning, high proportions of vegetation coverage, multi-layered planting, and a strong emphasis on ecological functionality. In residential areas, private garden planning often lacks these features, resulting in substantially lower CSD compared to parks.

Notably, around Budapest, at least one-third of residential areas contain significant private garden green space. Even within the study areas, CSD varied significantly—Oázis had nearly three times the CSD of Toldi and Malomárok. This underscores the substantial CS potential of Budapest's residential green spaces, which could be further enhanced through improved planning and management.

Table 1: Carbon storage density statistics of green space in different regions

Region or City	Carbon Storage Density (kg/m^2)	Source
Toldi (2022)	0.14	This study
Oázis (2022)	0.31	This study
Malomárok (2022)	0.13	This study
The whole Beijing city, China	0.78	(SUN et al. 2019)
The whole Xi'an city, China	0.28	(YAO et al. 2015)
71 Parks, in Daegu and Daejeon, South Korea	2.99	(JO et al. 2023)

The first quadrant reflects an expected trend, with increases in green space percentage corresponding to gradual increases in CS. Similarly, the third quadrant shows that reductions in green space percentage are associated with declines in CS, confirming the positive relationship between green space percentage and CS (Fig. 8).

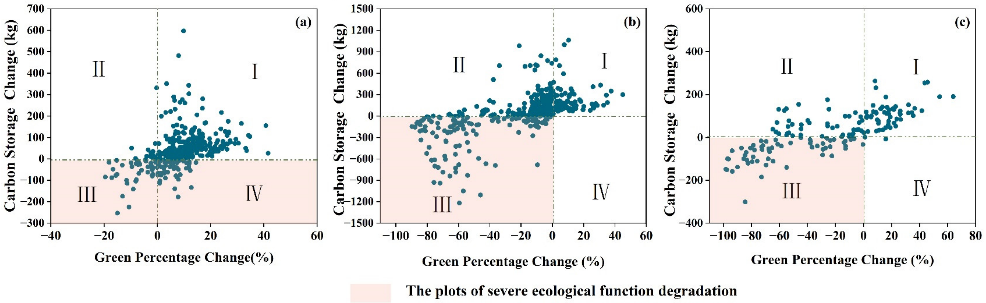

Fig. 8: Quadrant analysis of the relationship between green percentage change and Carbon storage change. (a) Toldi; (b) Oázis and (c) Malomárok.

A notable finding is that many plots in Oázis and Malomárok fall within the third quadrant, indicating significant green space loss. This is partly due to the conversion of undeveloped green areas into residential spaces between 2015 and 2022. Nonetheless, it underscores the need for better green space management to minimize loss during residential development. In contrast, some plots in Toldi are situated in the fourth quadrant, where increases in green space percentage coincide with declines in CS. This trend may be attributed to poor green space planning, such as the removal of large trees or the conversion of dense trees and shrub areas into lawns. Therefore, for private gardens, outreach and education initiatives could encourage residents to adopt practices that enhance the carbon storage capacity of their green spaces.

Plots in the second quadrant demonstrate the resilience of CS to reductions in green space percentage. For example, plots 1 and 6 in Figure 7 demonstrate that preserving existing trees and planting new ones can enhance carbon storage capacity, even when the overall green space percentage decreases. This reinforces the importance of scientifically-informed and well-executed green space planning in maximizing the CS potential of UGSs (Fig. 8).

5 Conclusion

This study used high-resolution near-infrared orthoimagery and a normalized surface model, combined with a tree height–carbon storage model, to assess spatiotemporal variations in green space CS across three newly developed residential areas in the Budapest metropolitan region. The key findings are as follows:

1. Spatiotemporal variations: From 2015 to 2022, the CS and CSD in the three residential areas exhibited significant spatiotemporal variations. The mapped CS data provides a valuable tool for urban planners, enabling precise identification of areas with limited carbon storage capacity.
2. Green Percentage change and Carbon Storage Correlation: A strong positive correlation was found between green space percentage changes and CS. However, moderate green space loss did not always reduce CS, while poorly planned increases could lower it. This highlights the need to integrate CS considerations into residential green space planning to enhance ecological function.

3. Methodological Framework: This study presents a practical CS estimation method that combines high-resolution satellite imagery with existing CS models. Given that this data is updated every three years across Hungary, the approach can be scaled for nationwide CS monitoring. The introduction of the "green certificate" aims to strengthen local green space regulations and enhance its role in construction approvals, ultimately improving the carbon storage capacity of real estate properties.

In conclusion, this research uses three newly developed residential areas as case studies to provide substantial evidence and a methodological framework for carbon storage monitoring across Hungary. Furthermore, it offers theoretical contributions to designer aimed at enhancing the carbon storage capacity of UGSs. By supporting sustainable urban planning and climate change mitigation, this study aligns with the European Union's goals for sustainable urban development.

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