The integration of multi-source 3D data for heritage greenery inventory and monitoring in the Royal Castle in Warsaw

Adam Kostrzewa [1,2], Anna Płatek-Żak [1], Agnieszka Żukowska [3], Jakub Markiewicz [1], Michał Kowalczyk [1], Agnieszka Bocheńska [3], Dorota Zawieska [1]

[1] Warsaw University of Technology, Faculty of Geodesy and Cartography, Plac Politechniki 1, 00-661 Warsaw, Poland - (adam.kostrzewa.dokt, anna.platek, michal.kowalczyk, jakub.markiewicz, dorota.zawieska)@pw.edu.pl
[2] Institute of Civil Engineering, Warsaw University of Life Sciences, Nowoursynowska 166, 02-787 Warsaw, Poland – adam_kostrzewa@sggw.edu.pl
[3] The Royal Castle in Warsaw – Museum, Warsaw, Poland - (azukowska, abochenska)@zamek-krolewski.pl

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Abstract: The article presents an approach for multisensors integrating data, namely terrestrial laser scanning (TLS; Leica RTC360), the MandEye mobile SLAM system equipped with a Livox MID-360 LiDAR sensor, and multi-temporal RGB and colour-infrared (CIR) aerial imagery supported by Airborne Laser Scanning (ALS) point clouds, for the detailed inventory of historical gardens and monitoring the process of rebuilding the bosquets in the Lower Gardens of the Royal Castle in Warsaw. The Castle Gardens constitute a unique cultural landscape of exceptional historical and symbolic value, where fragments of pre-war hornbeam bosquets have survived and now form the basis for contemporary restoration efforts. The study demonstrates how the integration of complementary active and passive sensing techniques enables a multi-scale, three-dimensional documentation of vegetation structure, capturing both fine-scale geometric details and broader spatial context. TLS data provide high-precision representations of tree geometry and hedge structure, while mobile SLAM measurements allow rapid mapping of garden interiors and hard-to-access areas. These ground-based datasets are complemented by ALS and photogrammetric point clouds derived from archival and contemporary aerial imagery, enabling the analysis of canopy structure and long-term vegetation growth. Additionally, CIR images were utilised to derive vegetation indices, supporting the assessment of plant vitality and temporal changes in biological condition. The results demonstrate that the proposed multi-source integration framework allows effective monitoring of spatial development, height growth, and health condition of reconstructed bosquets. The approach provides a robust methodological basis for heritage greenery inventory and long-term conservation monitoring, supporting informed decision-making in the management of historic gardens.

1. Introduction

The Royal Castle and its Gardens are a unique monument of architecture and garden art, as well as a symbol of Polish identity, determination, and the continuity of national heritage. After the destruction of World War II, the Castle was rebuilt and opened to the public in 1984. An aerial photograph from 1944 shows the destruction of the Royal Castle and the surviving bosquets (Figure 1). Today, the site is listed in the Mazovian Provincial Conservator of Monuments register, on the UNESCO World Heritage List, and within the boundaries of the "Historic Centre of Warsaw" Cultural Park (Szafrańska, 2017).

The Castle Gardens are part of the European Network of Historic Gardens and the European Garden Heritage Network. After years of neglect, the "reborn garden" has evolved into a space that combines culture, nature, and history. It is a place of exceptional importance for the capital's identity. The Upper Garden was reconstructed and reopened in 2015, and the restoration of the Lower Garden was finalised in 2019, completing the revival of the Castle's historic garden complex. Both parts form a coherent whole, providing an excellent setting for the Royal Castle and enriching its educational and cultural offer. They are visited by approximately 600,000 people annually, and admission to the gardens is free.

The Lower Garden, where fragments of historic bosquets (hornbeam hedges formed in the 1930s) have been preserved, is significant for contemporary research. Sixty-two trees from the original plantings have survived and today serve as a living testimony to the continuity of the landscape and the memory of the place. Bosquets, derived from the French word bosquet ("grove"), are a characteristic element of Baroque garden design - shady, secluded spaces where aesthetics, geometry, and nature create a harmonious whole.

Figure 1. An aerial image taken by the Luftwaffe in 1944 shows the ruins of the Royal Castle in Warsaw (outlined in yellow) and the Castle Gardens area with preserved bosquets (outlined in green).

The Castle Gardens, situated on the Vistula escarpment, possess a unique blend of natural, cultural, and symbolic significance.

They are an example of the harmonious coexistence of nature and heritage, and their history (from Renaissance designs to contemporary restoration) reflects the changes in styles, tastes, and values of successive eras. Like the Castle, the Gardens' reconstruction is a perfect example of historical restoration.

The origins of the Royal Castle Gardens in Warsaw date back to the 15th century, when they accompanied the residence of the Dukes of Mazovia, serving as purely utilitarian gardens. In the 16th century, the Castle became a royal residence, and the existing Renaissance-style garden was situated on a steep slope descending to the Vistula River, which flowed at its foot. It was divided into two regular sections, enclosed by a wooden fence. Aromatic, medicinal, and flowering plants grew within it, bounded by molded hedges, as well as shrubs and trees trimmed in ceramic pots. An important part of the garden was the orchard.

The character of the garden was influenced by the then Queen Anna Jagiellon, daughter of Queen Bona of the Italian Sforza dynasty (Bogucka, 1994; Pawłowska-Kubik et al., 2024). In subsequent centuries, the garden underwent transformations in accordance with prevailing fashions and the wishes of the current rulers (Szafrańska, 1988). A significant moment in its development was the expansion of the area to include the lower section beneath the escarpment, made possible by the shifting of the riverbed (late 17th century) and the subsequent construction work. The first partially implemented project for the Lower Garden, dating from the 1830s, did not last long due to the historical and political situation in Poland at the time. Power in Warsaw at that time was held by the viceroy of the Russian Tsar Alexander I.

Only after Poland regained independence in 1918 could work begin on restoring the Castle building, which became the official residence of the country's president (Szafrańska, 2015). The project to modernize the Upper and Lower Gardens began in 1937 (Szyszko-Bohusz, 1937). The design concept involved a harmonious blend of three styles: Baroque, Classicism, and 1930s Modernism. Key elements of the Baroque-inspired composition included a centrally located grassy indenter and symmetrical bosquets made of molded hornbeams (*Carpinus betulus*).

The already advanced work was interrupted by the outbreak of World War II. The castle did not survive the five-year war – it was completely destroyed. However, a significant portion of the garden was undamaged. Poles waited 40 years for the reconstruction of the castle, but they had to wait much longer for the restoration of the gardens – the rebuilt Lower Garden was opened to the public 74 years after the end of the war. The basis for the new design (Zemła, Zwiech, 2013-2014) for Garden reconstruction were pre-war plans and documents, as well as preserved trees from pre-war bosquets. The location of the Royal Castle in Warsaw, the gardens, and the bosquets themselves, with the original trees planted in 1937 – is visible in the Figure 1. Below, Figure 2 presents a location of the bosquets within OpenStreetMap and aerial imagery.

In this context, the documentation and monitoring of bosquets are critical. The restoration, protection, and documentation of cultural heritage are processes that extend far beyond the technical dimension. Spatial analysis, 3D modelling, and long-term monitoring are becoming modern conservation tools, enabling the continuous tracking of changes and the planning of protective measures based on actual information, rather than relying solely on visual observations (e.g., Murtiyoso et al., 2022; Markiewicz et al., 2025). In the case of the Lower Gardens of the Royal Castle, this approach enables us to capture the dynamics of hornbeam bosquet development, including both its spatial structure and the biological condition of the tree stand.

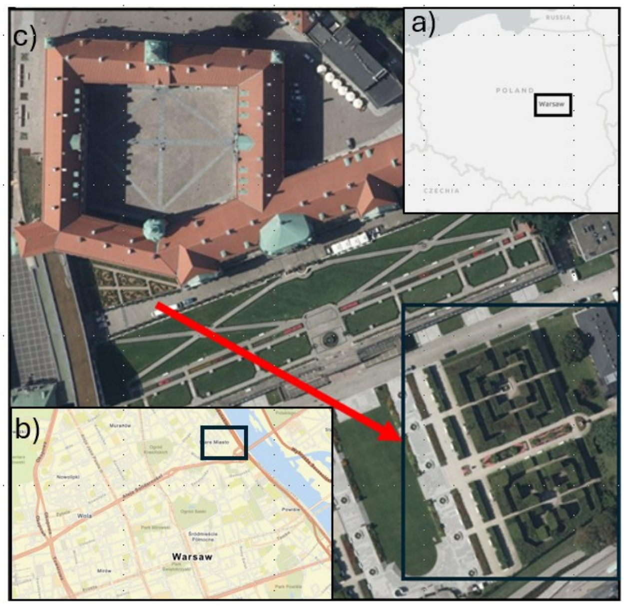

Figure 2. Location of the bosquets within (a) Central Europe and (b) the city of Warsaw (OpenStreetMap), (c) with the delineation of the Royal Castle and the Lower Gardens as shown on aerial imagery.

2. Materials and Methods

2.1 Multi-source spatial data

The spatial data were acquired using complementary active sensing techniques, combining terrestrial, mobile, and airborne laser scanning. The integration of these datasets enabled a comprehensive three-dimensional documentation of the study area, capturing h both the detailed local geometry of the vegetation and its broader spatial context across multiple scales.

The TLS survey was acquired by the Leica RTC360 3D laser scanner, which operates at a wavelength of 1550 nm. The scanner offers a measurement range of 0.5 to 130 meters (with the medium resolution option) and provides a spatial sampling of approximately 6 mm at a distance of 10 meters. The distance measurement accuracy is 1.0 mm plus 10 ppm, with an angular accuracy of 18 arcseconds, resulting in a three-dimensional (3D) point accuracy of about 1.9 mm at 10 meters. The TLS campaign was conducted on 13 June 2025. The documentation of the bosquets required 29 individual scan positions, resulting in a final point cloud exceeding 234 million points (Fig. 4). This dense terrestrial dataset provided the basis for a detailed analysis of the vertical structure and spatial relationships within the garden's tree stands.

The Mobile Mapping Survey (MMS) was carried out on the same day, 13 June 2025, using two MandEye systems, which are an open-hardware, open-source platform for real-time 3D data acquisition. Each system was equipped with a Livox MID-360

LiDAR sensor featuring a 360° horizontal and 300° vertical field of view. Depending on surface reflectivity, the sensor's effective range varies from approximately 40 meters for objects with 10% reflectance to about 70 meters for highly reflective surfaces (80%). The MandEye system operates using the HDMapping software framework, an open-source, end-to-end solution for large-scale 3D mobile mapping based on open-hardware hand-held, wearable, or mountable measurement devices. The MandEye systems operate using adaptive SLAM algorithms, which combine LiDAR odometry, pose graph optimisation, and techniques such as Normal Distribution Transform (NDT) and Iterative Closest Point (ICP) for trajectory correction and map alignment (Będkowski et al., 2025). The HDMapping framework integrates LiDAR–Inertial Odometry (HDMapping_LIO), pose graph SLAM for large-area mapping (HDMapping_Pose_GRAPH_SLAM), and advanced georeferencing strategies based on GNSS-RTK, control points, ground control points, and the integration of TLS and ALS data (HDMapping_Georeferencing). The dual-sensor configuration covered a total trajectory length of approximately 900 meters, providing continuous, high-resolution 3D mapping along the garden paths.

In addition to the ground-based measurements, archival Airborne Laser Scanning (ALS) datasets were used as a reference and contextual data source. The ALS point clouds were acquired within aerial surveying programmes and represent standard high-resolution airborne LiDAR products collected for topographic mapping and environmental monitoring purposes. The datasets were obtained using different sensor platforms and acquisition campaigns conducted in 2018, 2022, 2023, and 2025, with point densities ranging from 12 to 15 points/m² (Tab. 1). These multi-temporal ALS data provided consistent coverage of the entire Castle Gardens area and ensured reliable representation of the upper canopy layers and overall spatial structure of the vegetation.

Acquisition year	Point density	Sensor
03.04.2018	12 pts/m^2	RIEGL VQ-1560i-DW
09.05.2022	15 pts/m^2	Leica CityMapper-2
05.09.2023	12 pts/m^2	RIEGL VQ-780II
27.04.2025	12 pts/m^2	Leica CountryMapper-S

Table 1. Main characteristics of ALS datasets used in the study

Finally, the close-range measurements were integrated with archival ALS data acquired in 2018, 2022, 2023, and 2025 using the HDMapping_Georeferencing module, ensuring complete spatial coverage and multi-scale consistency. The integration of terrestrial, mobile, and airborne LiDAR point clouds provided a robust, multi-resolution representation of the study area, enabling accurate georeferencing and validation of TLS and SLAM datasets while ensuring metric precision at the local scale and spatial continuity at the landscape level, which formed the basis for subsequent analyses of the geometric and temporal dynamics of the reconstructed historical gardens.

In addition to active sensing techniques, the research employed optical data from aerial imagery acquired between 2017 and 2025. The dataset included both RGB and CIR images, which provided valuable spectral and spatial information for documenting the condition and structure of the study area. Depending on the flight campaign and sensor configuration, the Ground Sampling Distance (GSD) of the images ranged from 5 to 25 cm (Tab. 2), allowing for detailed analysis of surface features and vegetation cover. The RGB imagery was processed utilising Multi-View Stereo (MVS) algorithms to generate dense point clouds, which served as a complementary source of 3D information. The CIR images were crucial for assessing the health and vitality of vegetation because the near-infrared spectral band enabled the calculation of vegetation indices, including the Normalised Difference Vegetation Index (NDVI), providing additional information for environmental and landscape studies.

Acquisition year	Sensor	GSD	Type
18.05.2017	Leica DMC III	25 cm	RGB
07.07.2017	Leica DMC III	25 cm	CIR
07.04.2018	Leica DMC III	8 cm	RGB, CIR
03.04.2019	Leica DMC III	8 cm	RGB
05.04.2020	Vexcel UltraCam Eagle M3	5 cm	RGB, CIR
28.04.2021	Vexcel UltraCam Eagle M3	5 cm	RGB
09.05.2022	Leica CityMapper-2	5 cm	CIR
05.09.2023	Vexcel UltraCam Eagle M3	5 cm	RGB
18.07.2024	Leica DMC III	25 cm	RGB
27.04.2025	Leica CountryMapper-S	5 cm	RGB

Table 2. Main characteristics of aerial imagery datasets used in the study

2.2 Data processing

The processing workflow integrated photogrammetric and LiDAR datasets to ensure a consistent and comparable spatial framework for analysis. The archival aerial imagery used in this study was provided by the Main Office of Geodesy and Cartography and had been previously oriented within official production workflows, resulting in a fully adjusted photogrammetric block. This allowed the photogrammetric processing to focus exclusively on dense image matching and point cloud generation. The aerotriangulation file was natively imported into Trimble Inpho (version 9.1), where the dense reconstruction was performed. The exterior orientation parameters derived from the aerotriangulation were additionally exported and imported into Agisoft Metashape (version 2.1.3.) to enable parallel processing using more recent multi-view stereo (MVS) algorithms, reflecting the methodological evolution between the legacy Inpho environment (2013) and the contemporary Metashape implementation (2025). These dense reconstructions provided detailed surface representations, complementing the active LiDAR data and enabling three-dimensional analysis of the spatial structure of the Castle Gardens.

Trueorthos were produced for both RGB and CIR image sets. The CIR imagery, which includes the near-infrared spectral band, was used to calculate vegetation indices sensitive to plant vigour and chlorophyll content. All spectral analyses were performed in ArcGIS Pro (version 3.0.3). Two indices were computed:

- NDVI highlights differences in vegetation density and overall greenness by contrasting near-infrared and red reflectance values, providing insight into the health and vitality of plants.
- GNDVI, which utilises the green spectral band instead of the red, provides higher sensitivity to variations in chlorophyll concentration and thus enables a more detailed assessment of the physiological condition of vegetation.

These indices enabled the visual and quantitative analysis of vegetation patterns and temporal changes in plant condition across different datasets (Nițu et al., 2025).

2.3 Methods

The analytical workflow was based on the comparative analysis of point clouds derived from different sensing techniques, including TLS, mobile SLAM, ALS, and photogrammetric reconstruction from aerial RGB imagery. The primary objective was to evaluate both temporal changes in the structure of the bosquets and methodological differences resulting from the applied data acquisition techniques.

First, point clouds from all sources were co-registered within a unified spatial reference framework and clipped to identical spatial extents to ensure comparability. For each dataset, height models of the bosquets were generated, enabling the analysis of spatial and temporal variations in vegetation height between survey epochs. Comparisons between datasets acquired in different years allowed the assessment of vegetation growth dynamics, while comparisons between datasets acquired using different techniques enabled the evaluation of their respective geometric representation capabilities.

Cross-sectional analyses were then performed across selected transects of the bosquets. The cross-sections were used to examine differences in vertical structure, canopy shape, and point distribution between TLS, SLAM, ALS, and photogrammetric datasets. Particular attention was paid to the comparison of the inner and outer walls of the bosquets. The inner sides, characterised by limited accessibility and restricted sensor visibility, provided a test case for evaluating data completeness and point density under challenging acquisition conditions, in contrast to the outer walls, which were more easily observable by all sensing techniques.

Point density and completeness analyses were conducted within these cross-sections to quantify variations in sampling density and structural continuity. This allowed for a systematic comparison of the effectiveness of individual data sources in capturing dense vegetation structures and formed hedges.

In addition to profile-based analyses, volumetric calculations were performed for selected fragments of the bosquets. Vegetation volumes were estimated from point cloud–derived surface models and compared across different acquisition years and sensing techniques to assess both growth-related changes and methodological differences in volume representation.

Furthermore, differential surface models were generated by subtracting digital surface models (DSMs) from different epochs. These differential models enabled spatially explicit identification of vegetation growth and structural changes over time. To complement the geometric analyses, spectral information from CIR aerial imagery was used to compute vegetation indices, including NDVI and GNDVI. These indices supported the assessment of vegetation vitality and physiological condition and allowed the integration of structural and biological indicators in the analysis of the reconstructed historical garden.

3. Results

3.1 Data pre-processing

TLS data acquired simultaneously with SLAM provided the opportunity to measure the current state of vegetation. Several TLS stations were located in the upper part of the Royal Gardens, allowing for the measurement of the upper sections of vegetation, which reached heights of approximately 6 meters. From ground level, using TLS (or SLAM) techniques, it was not possible to capture the upper parts of the vegetation. Below (Figure 3) is an RGB visualisation of the TLS data limited to the bosquet area. The left section of the bosquets appears more complete (including the highest layers) than the right section, due to the use of TLS stations also located in the upper part of the gardens. Figure 4 presents a schematic layout of the stations in relation to the area of interest.

Figure 3. Point cloud acquired with the Leica RTC360 terrestrial laser scanner, showing detailed geometry of the bosquets

Registration of TLS data from 29 stations was carried out using Leica Cyclone REGISTER 360 software. The overlap was 45%, and the strength was 48%. The Global Bundle Error amounted to 0.003 m.

SLAM data were acquired independently with two scanners operated by different numbers of operators. This approach ensured that complementary datasets from multiple passes, recorded from various angles and directions, were obtained.

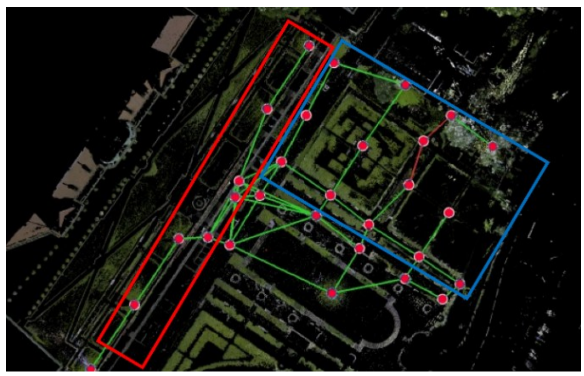

Figure 4. Map showing the distribution of TLS scan positions. The blue rectangle indicates the bosquet area, while the red rectangle marks the extent of TLS scan positions in the Upper Gardens

3.2 Data analysis point cloud data

This section presents the results of point cloud analyses performed to evaluate the geometric completeness, structural representation, and variability of the bosquets as a function of data acquisition technique, sensor type, and acquisition year.

3.2.1 Cross-section

The first group of analyses consisted of longitudinal and transverse cross-sections through the walls of the bosquets. These cross-sections were used to assess the completeness, point density, and structural variability of the point clouds obtained using different sensing techniques, as well as their temporal consistency across datasets acquired in different years.

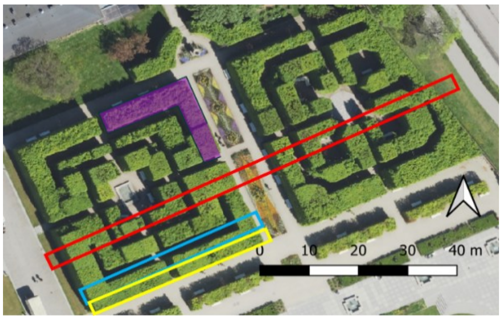

Figure 5. Location of the analysed cross-sections within the study area. The red line represents the longitudinal cross-section used for inter-annual and inter-technique comparisons, while the blue and yellow lines denote transverse cross-sections through the inner and outer bosquet walls, respectively. The purple polygon indicates the area selected for volumetric analysis.

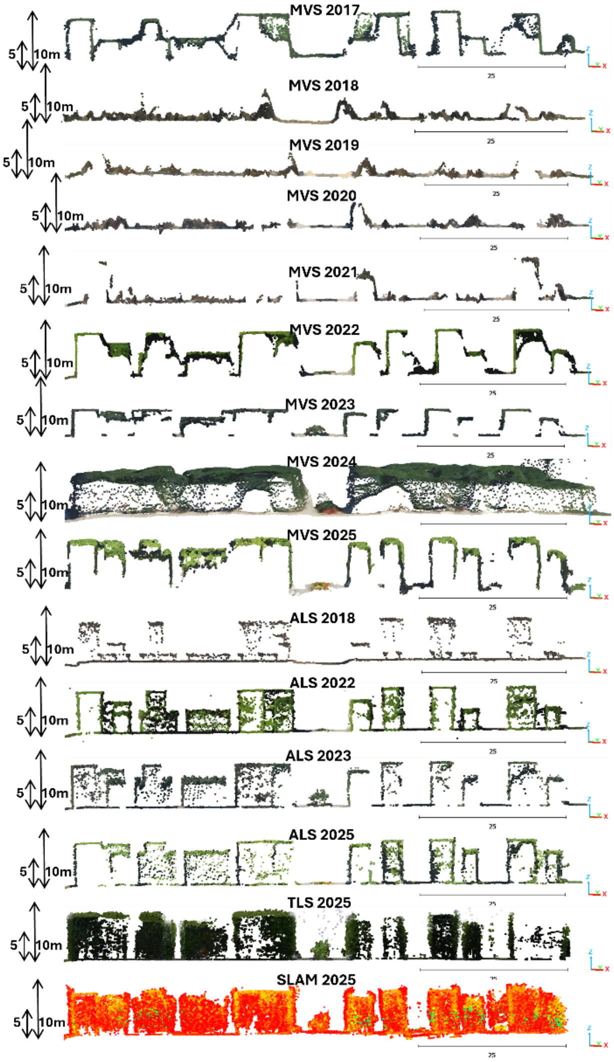

Figure 6. Comparison of height profiles obtained from different sensors and acquisition years along the longitudinal cross-section indicated in Figure 5 (red outline).

Figure 5 illustrates the spatial location of the analysed cross-sections. The red line indicates the main longitudinal cross-section used for the comparison of datasets from different acquisition techniques and epochs. The blue and yellow lines represent transverse cross-sections through the inner and outer walls of the bosquets, respectively, which were used to analyse point density and data completeness. The purple polygon delineates the area selected for volumetric analyses described in the following sections.

The longitudinal cross-section illustrating the variability of point cloud representation depending on the acquisition technique and data recency is shown in Figure 6. An evaluation of the ALS point clouds acquired in different years reveals a high level of geometric consistency and a relatively uniform spatial distribution of points across all epochs. The TLS and SLAM datasets acquired in 2025 provide very dense and complete representations of the lower and middle parts of the bosquets; however, limitations of ground-based techniques are visible in the upper canopy layers, where data gaps occur due to restricted sensor range and occlusions.

The MVS-derived point clouds exhibit the highest variability in terms of completeness and geometric quality. Their quality strongly depends on the ground sampling distance (GSD) of the source imagery (5, 8, or 25 cm; Table 2). As a passive sensing technique, aerial photogrammetry primarily captures the upper parts of the vegetation, resulting in a lack of information from the vertical walls of the bosquets. Additionally, significant reconstruction deficiencies were observed in the MVS point clouds generated from imagery acquired between 2018 and 2021. Despite testing multiple dense matching strategies and software packages—including Agisoft Metashape, Trimble Inpho, OpenMVS using Patch-based and SGM approaches (OpenMVS, 2026), and RealityScan mesh-based point generation these datasets remained incomplete in the analysed areas. Consequently, MVS data from the years 2018–2021 were treated with caution and excluded from selected quantitative analyses due to their limited reliability.

In the next step, the completeness and point density of the bosquet walls were analysed in more detail using transverse cross-sections. Two wall types were examined: the outer wall of the bosquets (yellow outline in Figure 5), characterised by unobstructed access and visibility, and the inner wall (blue outline in Figure 5), located along narrow paths between bosquets (approximately 1 m wide), where accessibility for ground-based techniques is limited.

This configuration allowed a direct comparison of data completeness and point density under contrasting acquisition conditions, highlighting differences between ground-based techniques (TLS and SLAM) and airborne approaches (ALS and MVS). The transverse cross-sections through both wall types for the same fragment of the bosquet are presented in Figure 7.

The cross-sectional analyses clearly reveal the limitations of individual data sources. MVS point clouds show pronounced data gaps along the vertical walls of the bosquets. Ground-based TLS and SLAM datasets, while dense and detailed at lower heights, exhibit reduced coverage of the upper canopy, particularly along the inner walls where acquisition geometry is constrained by limited space. In contrast, ALS data provide the most uniform and complete representation of both the inner and outer walls, with a consistent point distribution and returns from all vertical zones of the vegetation.structure. In contrast, photogrammetric MVS data tend to smooth object boundaries and exhibit reduced sensitivity to vertical vegetation surfaces, resulting in lower completeness and density along the bosquet walls.

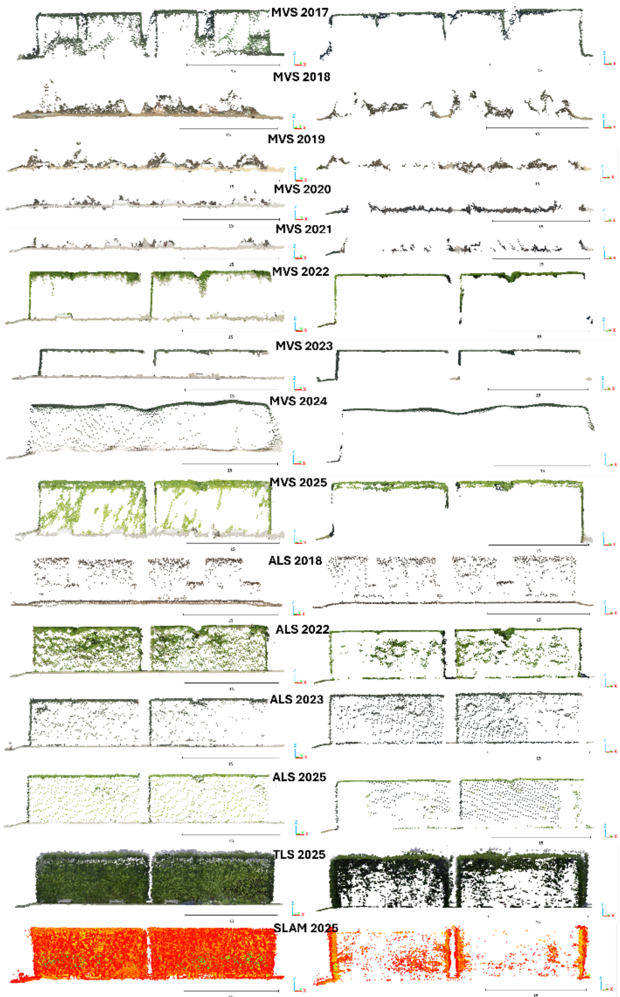

Figure 7. Transverse cross-sections through the same fragment of the bosquet, showing the outer wall (right; yellow outline in Figure 5) and the inner wall (left; blue outline in Figure 5), derived from different sensing techniques.This configuration allowed a direct comparison of data

3.2.2 Volumetric analysis of the bosquets

Volumetric analyses were performed to quantify changes in the spatial development of the bosquets and to compare the impact of different data acquisition techniques on volume estimation. The calculations were carried out for a selected fragment of the bosquet delineated by the purple polygon shown in Figure 5. Due to substantial completeness deficiencies observed in the MVS-derived point clouds from the years 2018–2021, these datasets were excluded from the volumetric analysis to ensure the reliability and Vegetation volumes were calculated using the Compute 2.5D Volume tool implemented in CloudCompare software. This method estimates volume differences between a reference plane and a surface derived from a point cloud by rasterising the data into a regular grid and integrating height values within each grid cell. The approach is well suited for analysing volumetric changes in vegetation structures, as it provides robust and comparable results across datasets with different point densities, provided that the same spatial extent and grid resolution are applied.

All point clouds were clipped to identical spatial boundaries corresponding to the selected bosquet fragment, and the same processing parameters were used for all datasets to minimise methodological bias. The volumetric results obtained for different sensing techniques and acquisition years are summarised in Table 3.

Dataset	Number of points	Volume [m^3]
MVS 2017	18 948	10 900
MVS 2022	26 964	11614
MVS 2023	100 651	11 141
MVS 2024	2 512	11 117
MVS 2025	46 972	13 387
ALS 2018	3 882	11 432
ALS 2022	25 769	12 777
ALS 2023	6 504	13 044
ALS 2025	3 791	13 441
SLAM 2025	213 803	13 795
TLS 2025	11 104 444	13 590

Table 3. Vegetation volume estimates for the selected bosquet fragment derived from different sensing techniques and acquisition years.

The results indicate a general increase in the volume of the analysed bosquet fragment over time, reflecting ongoing vegetation growth and the progressive development of the reconstructed garden structure. This trend is consistently observed across both airborne and ground-based datasets, despite differences in point density and acquisition geometry.

Noticeable differences in volume estimates are observed between data acquisition techniques. Volumes derived from MVS point clouds are generally lower and exhibit greater variability, particularly in earlier datasets. This can be attributed to the smoothing of vegetation boundaries and the limited ability of passive photogrammetric methods to reconstruct vertical surfaces and fine structural details. Nevertheless, the primary advantage of aerial imagery lies in its availability across multiple historical periods, which enables long-term retrospective analyses of vegetation dynamics despite limitations in geometric detail. ALS-derived volumes show higher consistency and a clearer temporal trend. Airborne LiDAR provides a reliable representation of canopy geometry and overall vegetation structure, resulting in stable volume estimates across different years. However, the temporal resolution of ALS data is constrained by the availability of acquisition campaigns, limiting its applicability for short-term monitoring.

Ground-based datasets (TLS and SLAM) yield the highest volume estimates, reflecting their ability to capture dense and detailed representations of vegetation, including lower and intermediate layers that are partially occluded or poorly represented in airborne datasets. TLS provides the most detailed geometric reconstruction, preserving fine-scale structural features, while SLAM offers a balance between acquisition efficiency and geometric completeness. The slight differences between TLS- and SLAM-derived volumes are primarily related to variations in point density, viewing geometry, and the inherent limitations of mobile mapping in densely vegetated environments. Overall, the results demonstrate that while absolute volume estimates differ between sensing techniques, the integrated multi-source approach enables a coherent interpretation of vegetation growth trends. Combining archival airborne data with contemporary ground-based measurements provides a comprehensive framework for analysing both long-term changes and current structural conditions of historic garden vegetation.

3.2.3 Digital Surface Models and differential analysis

Height models were generated from point clouds derived from different acquisition techniques and survey epochs to quantify vertical changes in the vegetation structure of the bosquets. Digital surface models (DSMs) computed for individual datasets enabled the calculation of differential height models, providing a spatially explicit representation of vegetation growth over time.

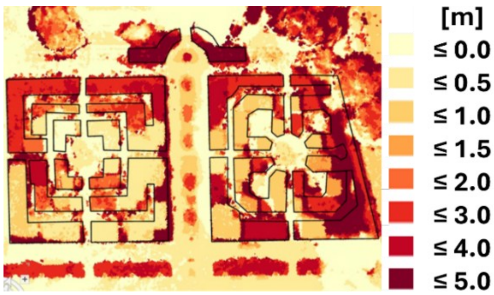

Figure 8. Differential height model illustrating vegetation growth derived from DSMs generated from MVS-based point clouds from aerial imagery acquired in 2017 and 2023.

Figure 8 presents a differential model calculated from DSMs derived from MVS-based point clouds generated from aerial imagery acquired in 2017 and 2023. The model illustrates height differences corresponding to vegetation growth between the two acquisition dates. Although MVS point clouds exhibit limitations in terms of completeness and structural detail, the DSMs derived from aerial imagery provide reliable information on the upper vegetation layer. As a result, differential DSM analysis proves to be an effective method for identifying and visualising vertical growth patterns of the bosquets at the canopy level.

3.3 Vegetation index analysis

Vegetation condition was assessed using spectral information from colour-infrared aerial imagery by calculating the NDVI and the GNDVI. These indices provide indicators of vegetation vitality and chlorophyll content and complement the geometric analyses based on point clouds and height models. Shadowed areas were identified and masked to improve the reliability of vegetation index interpretation. The results of NDVI and GNDVI calculations are presented in Figure 9.

The analysis revealed that, despite shadow masking, radiometric heterogeneity still affects vegetation index values, particularly in areas with dense vegetation and complex canopy structure. Consequently, the reliability of vegetation indices strongly depends on image spatial resolution. Aerial imagery with a ground sampling distance (GSD) of 25 cm proved insufficient for detailed vegetation analysis at the scale of individual bosquets, whereas datasets with finer spatial resolution (5 cm and 8 cm GSD) provided more consistent and interpretable results.Example visualisations of NDVI and GNDVI derived from aerial imagery acquired in 2017 and 2022 are presented in Figure 9, illustrating spatial variability in vegetation condition and the influence of image resolution on index interpretation.

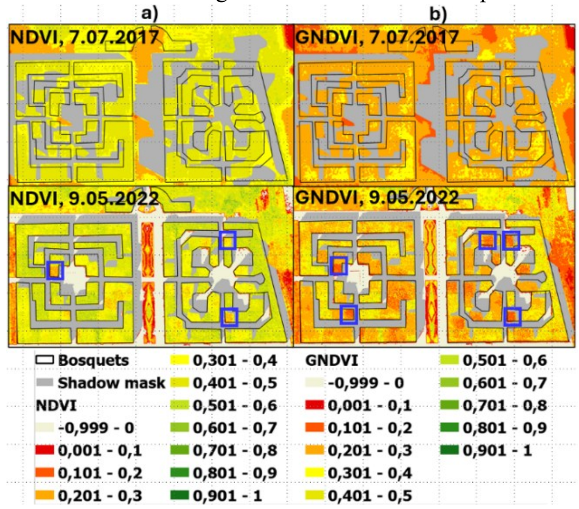

Figure 9. Examples of visualisations: (a) NDVI and (b) GNDVI derived from colour-infrared aerial imagery acquired in 2017 and 2022. Lower NDVI and GNDVI observed in the 2022 dataset compared to 2017, highlighted with blue frames, suggest potential changes in vegetation condition and chlorophyll content.

Based on the visual analysis presented in Figure 9 (a), the NDVI map derived from the 2017 imagery exhibits relatively uniform values. This homogeneity may result from the coarser spatial resolution of the input data as well as the phenological stage of vegetation at the time of image acquisition. NDVI results obtained from the 2022 dataset show substantially greater spatial variability, reflecting differences in vegetation condition. Areas characterised by lower NDVI values are highlighted with blue frames in Figure 9 and may indicate reduced vegetation vitality, lower chlorophyll content or stress related to water availability or management practices.

A similar pattern is observed for the GNDVI results (Figure 9 (b)). The 2017 image yields relatively uniform GNDVI values. In comparison, the 2022 GNDVI maps reveal enhanced spatial differentiation. Lower GNDVI values, marked in blue frames, may point to reduced chlorophyll concentration, early signs of physiological stress, or variations in species composition and leaf structure.

4. Summary and conclusions

The restoration, protection, and documentation of cultural heritage extend beyond purely technical procedures and involve preserving memory, identity, and cultural continuity. In this context, contemporary heritage conservation increasingly relies on data-driven approaches while maintaining respect for the intangible values embedded in historic landscapes.

A central aspect of the proposed approach is the integration of interdisciplinary knowledge and multi-source spatial data. The combined use of TLS, mobile SLAM-based mapping, and RGB and CIR aerial imagery acquired at different times enables a comprehensive characterisation of historic vegetation, allowing both geometric structure and biological condition to be assessed.

Multi-temporal analyses based on heterogeneous datasets make it possible to investigate vegetation growth and change over time. LiDAR data play a key role in capturing the vertical structure of bosquets: ALS effectively represents upper canopy layers, while TLS and SLAM provide detailed information on the lower and intermediate parts of the vegetation. Their integration results in a complete, multi-scale representation of tree stand structure.

Point clouds derived from MVS photogrammetry are generally less detailed than LiDAR-based datasets; however, their major advantage lies in the wide availability of archival aerial imagery spanning several decades. This enables long-term comparisons and the analysis of vegetation dynamics across historical periods, supporting the reconstruction of development trends in garden landscapes.

TLS surveys provide high geometric accuracy and enable detailed analyses at the level of individual trees, but their application is limited by time requirements and line-of-sight constraints. These limitations are mitigated by mobile SLAM systems, such as MandEye, which allow rapid data acquisition in areas with restricted accessibility. Although SLAM-derived point clouds exhibit slightly lower accuracy, they effectively capture spatial relationships, hedge geometry, and the lower parts of bosquets.

Ground-based measurements are further complemented by ALS and photogrammetric data, which provide information on upper vegetation layers and the broader spatial context of tree stands (Płatek-Żak & Zawieska, 2023). The integration of TLS, SLAM, and aerial datasets results in a coherent, multi-resolution 3D representation of vegetation, supporting the assessment of temporal changes, restoration effectiveness, and future conservation planning (Markiewicz et al., 2018).

The analytical potential of the approach is enhanced by integrating geometric data with spectral information. Vegetation indices derived from RGB and CIR orthophotomaps, such as NDVI and GNDVI, enable the assessment of plant health and the identification of stressed vegetation, supporting maintenance and conservation decisions based on quantitative indicators.

Finally, the use of integrated datasets within a 3D GIS environment facilitates advanced geovisualisation and improves communication between researchers, conservators, and decision-makers. In this way, geoinformation technologies support informed and sustainable management of historic garden landscapes (Turek et al., 2018). Multi-temporal analyses of heterogeneous datasets enable the investigation of vegetation growth and change over time. LiDAR data play a central role in capturing the vertical structure of bosquets: ALS effectively represents the upper layers of tree crowns, while TLS and SLAM data provide detailed information on the lower and intermediate parts of the vegetation. The integration of these datasets results in a complete, multi-scale representation of the spatial structure.

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