A Multi-Sensor and Multi-Temporal Approach to 3D Documentation of Historic Gardens: A Case Study of Villa Burba, Italy

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Abstract

Historic gardens represent living heritage systems in which spatial configuration evolves through the interaction among vegetation dynamics, environmental conditions, and ongoing management. However, current 3D documentation approaches often treat these landscapes as static entities, limiting their ability to capture and interpret temporal transformations. This study proposes a multi-sensor, multi-temporal approach for the systematic documentation and monitoring of historic gardens, integrating UAV photogrammetry and mobile laser scanning (MLS) to enhance spatial completeness and analytical reliability.
Two survey campaigns conducted at Villa Burba (Italy) in 2023 and 2025 produced multi-temporal datasets acquired under different environmental conditions. Following multi-sensor integration and temporal harmonisation, point cloud comparison was performed using the Cloud-to-cloud (C2C) distances and Multiscale Model-to-Model Cloud Comparison (M3C2) methods to quantify spatial differences. The results demonstrate centimetre-level geometric consistency and improved ground coverage by integrating UAV and MLS data, ensuring reliable comparability between epochs. Based on this, spatial changes were identified, including variations in vegetation structure, tree-removal events, terrain modifications, and changes to the internal watercourse. These findings were validated against botanical surveys and maintenance records, confirming their consistency with documented management activities and environmental conditions. To support interpretation and accessibility, the multi-temporal datasets were further deployed in GIS and on the Cesium platform using 3D Tiles, enabling interactive exploration and long-term data use. This proposed approach demonstrates how integrating photogrammetry with complementary surveying techniques can support multi-temporal analysis, contributing to more informed monitoring and interpretation of historic gardens as evolving landscapes.

1. Introduction

Historic gardens embody a distinctive form of Cultural Heritage (CH) in which design, nature, and time are inseparably intertwined, while also constituting an integral component of cultural landscapes. Unlike architectural monuments, which preserve relatively stable geometries after being constructed, historic gardens are predominantly composed of living elements, including vegetation, soil, and water, which continuously evolve through biological growth, seasonal cycles, environmental change, and human management. Their spatial configuration is therefore not fixed, but reflects an ongoing process of transformation. This temporal dimension fundamentally distinguishes historic gardens from many other forms of CH. The value of a historic garden lies not only in its original design but also in the layered traces of ecological processes and maintenance practices that accumulate over time (Barthel et al., 2010). Trees mature and decline, vegetation patterns shift, water systems expand or contract, and management interventions reshape the landscape. As a result, the morphology of a historic garden evolves gradually, often in subtle but significant ways that are critical for its conservation and interpretation.
Traditional documentation methods have long attempted to record historic gardens through drawings, photographs, and descriptive inventories (Zakariya et al., 2024). While these materials remain essential sources of historical knowledge, most capture the landscape at a specific moment in time. Current digital documentation often follows a similar logic, as sites are typically surveyed once to produce highly detailed spatial models that represent a single state or a generalised condition for a given period. This approach is well-suited to relatively stable heritage forms such as architecture, monuments, and archaeological sites, but is less appropriate for historic gardens.
Advances in geomatics technologies have significantly expanded the possibilities for documenting complex landscapes. Among these technologies, UAV photogrammetry has become a widely used tool for recording cultural landscapes due to its efficiency and relatively low cost in generating high-resolution orthophotos and dense three-dimensional (3D) reconstructions (Pepe et al., 2022). Structure-from-Motion (SfM) photogrammetry enables detailed modelling of terrain morphology and, to some extent, vegetation canopy surfaces across large areas. However, its application in historic gardens presents specific challenges. Compared with more open environments, dense vegetation often causes occlusions that hinder the reconstruction of ground surfaces and vertical structures, both of which are critical to understanding the spatial organisation of gardens.
To address these limitations, increasing attention has been directed toward multi-sensor surveying approaches that integrate photogrammetric methods with LiDAR-based technologies. In particular, mobile laser scanning (MLS) systems provide dense terrestrial observations that capture under-canopy structures and ground-level features difficult to detect in aerial imagery. Compared with the commonly adopted combination of terrestrial laser scanning (TLS) and UAV photogrammetry, MLS offers greater efficiency for large-scale data acquisition due to its mobility and extended range, thereby enabling rapid, accurate, and non-invasive recording of complex

environments (Fassi and Perfetti, 2019). The integration of aerial photogrammetry and MLS, therefore, provides complementary spatial perspectives, significantly improving both the completeness and efficiency of 3D landscape documentation.

Yet the challenge of documenting historic gardens is not solely technical. As inherently dynamic landscapes, they should be documented to account for temporal change. Repeated surveys acquired at different times enable the observation of landscape transformation, allowing researchers and heritage managers to detect structural modifications, interpret ecological processes, and preserve digital records of elements that may eventually disappear. At the same time, integrating multi-temporal data with historical sources warrants further consideration, as it offers a meaningful way to incorporate time into the interpretation of historic gardens.

This study explores this perspective through the historic garden of Villa Burba, located in Rho, near Milan, Italy. Two survey campaigns conducted in 2023 and 2025 generated temporally comparable datasets using UAV photogrammetry and MLS. By integrating these datasets within a unified geospatial framework and analysing them through point cloud-based spatial comparison and Geographic Information System (GIS) knowledge, the study identifies changes in vegetation structure, terrain conditions, hydrological features, and maintenance-related interventions within the garden. The resulting multi-temporal datasets and analysis outputs were subsequently deployed in a web-based environment to support interactive exploration and long-term accessibility. In addition, botanical surveys and maintenance records provided by the site management authority were used to validate and support the interpretation of the detected changes.

This research proposes a multi-sensor, multi-temporal approach for observing and documenting historic gardens as evolving heritage landscapes, demonstrating how digital surveying technologies can effectively support their long-term monitoring, conservation, and management.

2. State of the Art

2.1 3D Survey for Historic Garden

3D surveying has been extensively applied in historic garden documentation, with multiple studies demonstrating improvements in capturing the spatial complexity of terrain, vegetation, and architectural elements. TLS, in particular, provides high geometric accuracy and detailed structural representation, supporting conservation assessment and restoration planning (Li et al., 2025a). However, its limitations in large-scale and densely vegetated environments are well documented. TLS workflows are often time-consuming and constrained by site accessibility, while dense vegetation causes significant occlusion, resulting in incomplete data, especially for understorey and ground surfaces (Chen et al., 2025; Hrdina et al., 2025). As a result, although TLS ensures high precision, its efficiency and scalability remain limited in complex historic garden contexts.

Photogrammetric methods, particularly UAV-based SfM, have been widely adopted to address coverage limitations. Research in archaeological landscapes and historic gardens has demonstrated that UAV photogrammetry enables rapid acquisition of high-resolution orthophotos and digital surface models, significantly improving spatial coverage and survey efficiency (Li et al., 2025a). These outputs have supported morphological analysis, vegetation mapping, and spatial planning at the landscape scale. However, limitations remain in vegetation-rich environments. UAVs cannot penetrate dense canopies, and occlusion reduces ground visibility, while reconstruction accuracy declines in areas with dense foliage or low texture. Consequently, although UAV photogrammetry enhances large-scale documentation, it often fails to capture the full vertical structure and ecological layering that characterise historic gardens.

Recent research has increasingly focused on multi-sensor integration, combining TLS, MLS, and UAV photogrammetry. Case studies in archaeological parks and historic gardens demonstrate that such approaches improve data completeness by reducing occlusion and enabling multi-scale representation (Li et al., 2024; Liang et al., 2018). MLS, in particular, has shown strong capability in capturing under-canopy structures and continuous ground profiles along pathways, complementing aerial data, as demonstrated in forested and complex built environments (Fassi et al., 2025; Wu et al., 2025). These integrated approaches produce more comprehensive 3D models, improving the representation of both vegetation and terrain. However, most studies remain focused on geometric accuracy and visualisation, with limited attention to analytical applications such as semantic classification, temporal monitoring, and decision support for conservation management.

2.2 Multi-Temporal Monitoring of Landscapes

Multi-temporal monitoring has significantly advanced through repeated 3D surveys, enabling quantitative assessment of landscape change. Studies using LiDAR and photogrammetry show that methods such as Cloud-to-cloud (C2C) distances, Multiscale Model-to-Model Cloud Comparison (M3C2), and Digital Elevation Models (DEM)/Digital Surface Models (DSM) differencing can detect subtle geomorphological and vegetation changes with high precision (Ozdas et al., 2024; Shafaat et al., 2025). In natural landscape case studies, such as river systems, coastal zones, and forest environments, these methods have successfully captured erosion patterns, vegetation growth, and terrain deformation, improving the understanding of dynamic processes (Kharroubi et al., 2022). However, their application to historic gardens remains limited. Existing studies primarily address natural processes and do not adequately consider design intentions and management-driven changes that shape these landscapes.

In historic garden contexts, some research has begun to explore repeated surveys to assess changes in vegetation volume, tree growth, and structural conditions, indicating the potential of multi-temporal datasets for monitoring designed landscapes. Nevertheless, these studies remain relatively scarce and often lack systematic temporal frameworks. Most existing applications rely on single-epoch documentation or irregular survey intervals, limiting their ability to capture long-term landscape evolution (Li et al., 2026). Furthermore, current approaches rarely integrate historical design intentions or maintenance records, resulting in a gap between geometric change detection and meaningful interpretation in the context of heritage values.

A major limitation in multi-temporal analysis of historic gardens is the impact of seasonal variability and vegetation dynamics on data comparability. Leaf-on and leaf-off conditions significantly affect point cloud density, canopy representation, and ground visibility, introducing inconsistencies across temporal datasets (Tupinambá-Simões et al., 2024). These variations complicate change detection, making it difficult to distinguish between seasonal effects and actual structural transformations. Further inconsistencies arise from variations in sensor types, acquisition parameters, and survey conditions. As a result, recent studies emphasise the need for standardised acquisition protocols and the integration of multi-source data, including botanical surveys, GIS layers, and maintenance documentation, to improve reliability and interpretation.

2.3 Multi-sensor Data Integration

From a methodological perspective, multi-sensor integration follows a sequential workflow of data acquisition, co-registration, and fusion within a unified coordinate framework. Activities integrating UAV photogrammetry, even UAV LiDAR, with terrestrial or mobile LiDAR demonstrate that initial alignment is typically achieved through Global Navigation Satellite System (GNSS) positioning and ground control points (GCPs), followed by fine registration using algorithms such as Iterative Closest Point (ICP) or feature-based matching (Liu et al., 2024). The effectiveness of this process has been validated in several landscape and heritage studies, in which integrated datasets exhibit improved spatial continuity and reduced occlusion compared with single-source data. LiDAR contributes reliable geometric measurements in under-canopy and low-texture areas, while photogrammetry enhances surface detail and coverage in open and elevated zones. In historic gardens, this complementarity supports a more complete reconstruction of multi-layered environments, including vegetation stratification, pathway networks, and embedded architectural elements (Liang et al., 2018). However, these workflows remain highly dependent on careful planning of acquisition geometry and control distribution to ensure consistency between datasets.
Despite these advances, methodological challenges remain significant in the integration process. Differences in point density, noise characteristics, and viewing geometry between LiDAR and photogrammetric datasets can lead to misalignment and local distortions during registration, particularly in vegetation-rich environments where stable features are limited (Sestras et al., 2025). In addition, the selection of registration parameters, scale harmonisation, and filtering strategies directly affects the quality of the fused dataset, yet these procedures are often not standardised. Temporal discrepancies further complicate integration, as vegetation growth and seasonal variation reduce feature correspondence and weaken the reliability of alignment. Consequently, while multi-sensor workflows improve geometric completeness, they also introduce uncertainties that may propagate into subsequent analysis.

2.4 Digital Platforms for Heritage Management

Digital platforms are increasingly used as operational tools for managing complex heritage landscapes, including historic gardens, where heterogeneous data should be integrated into coherent workflows. GIS-based systems have proven effective in structuring vegetation inventories, mapping spatial elements, and linking maintenance records to specific components, thereby supporting conservation decision-making (Jia et al., 2022; Redweik et al., 2022). In several European case studies, GIS platforms have enabled managers to monitor tree conditions, track interventions, and support restoration planning through spatial queries and attribute-based analysis (Cazzani et al., 2019; Li et al., 2026). More advanced approaches, such as 3D GIS and Heritage Building Information Modelling (HBIM) based framework, demonstrate potential for integrating geometric, semantic, and temporal information, enabling multi-layered representation of garden elements and their evolution (Jia et al., 2022). However, practical limitations remain. These systems could struggle to handle large-scale point cloud data directly, requiring simplification or conversion that reduces geometric detail. Moreover, their data models are typically oriented toward static architectural elements, limiting their ability to represent dynamic vegetation processes and multi-temporal change in historic gardens.
Web-based 3D platforms have addressed some of these limitations by enabling efficient visualisation and sharing of large geospatial datasets. Some studies using technologies such as Cesium (3D Tiles), Potree, and other cloud-based platforms demonstrate significant improvements in data accessibility, allowing stakeholders to interact with dense point clouds and 3D models directly through web interfaces (Li et al., 2025b, 2024). In heritage and landscape monitoring projects, these platforms support multi-user access, remote collaboration, and multi-temporal visualisation through layer-based or time-enabled interfaces, facilitating comparison between survey epochs and identification of spatial change. However, existing implementations remain largely focused on visualisation. Current case studies report limited support for analytical workflows, such as quantitative change detection, semantic classification, and integration with management data. In addition, multi-sensor datasets are often handled in a fragmented manner, with limited tools to ensure consistency across data sources and temporal states. These limitations highlight the need for integrated platforms that combine efficient 3D data streaming with analytical capabilities and structured heritage information, including the incorporation of historical records, to support systematic monitoring and management of historic gardens as evolving landscapes.

2.5 Research Gaps and Objectives

Existing studies predominantly focus on single-epoch modelling or isolated sensing techniques, with limited attention to integrating multi-sensor data under vegetation-rich conditions and to the challenges of ensuring temporal consistency across repeated surveys. Moreover, while multi-temporal change detection has been extensively developed for natural landscapes, its application to historic gardens remains limited, particularly in quantitative evaluation and validation against real management data. At the same time, digital platforms, especially web platforms, are often used for visualisation purposes but do not fully support the analytical and comparative exploration of multi-temporal datasets.
This study addresses these gaps by proposing a multi-sensor, multi-temporal, and quantitatively validated workflow that enables the systematic monitoring and interpretation of historic gardens as living heritage landscapes and bridges the divide between advanced geomatics technologies and practical conservation–management needs.

3. Methodology

3.1 Study Area and Datasets

3.1.1 Villa Burba: Villa Burba is a seventeenth-century villa complex with a historic garden covering approximately 16,000 m^2. The site represents a characteristic example of a mixed garden typology, in which architectural elements, vegetation, and water features are spatially and functionally integrated. Its current configuration includes tree-lined paths, open lawns, dense clusters of vegetation, and fountains and ponds, forming a heterogeneous and multi-layered spatial structure (Figure 1). The garden has undergone multiple phases of transformation over time, reflecting both historical design intentions and ongoing maintenance practices that continuously reshape its spatial organisation. As a living heritage landscape, Villa Burba is subject to continuous change driven by both natural processes and human interventions. Seasonal variations influence vegetation density and canopy structure, while maintenance activities, such as pruning, replanting, and infrastructure management, further modify the landscape. From a geomatics perspective, these dynamics pose significant challenges, including occlusions from dense vegetation, variable terrain conditions, and the limitations of single-sensor survey approaches in capturing complete spatial information. At the same time, the site's manageable scale, controlled environment, and availability of complementary data, including botanical inventories and maintenance records, make it a suitable site for evaluating multi-sensor and multi-temporal survey methodologies, as well as for validating detected changes and supporting the interpretation of landscape evolution in relation to conservation and management practices.

Figure 1. Study area: the historic garden of Villa Burba.

3.1.2 Survey Campaigns: Two multi-sensor survey campaigns were conducted at Villa Burba to capture its spatial configuration under different temporal and environmental conditions. The first survey, carried out in April 2023, represents a leaf-on state, characterised by relatively dense vegetation cover, complex canopy structure, and limited ground visibility, reflecting conditions during the active growing season. The second survey, conducted in November 2025, provides a contrasting dataset under reduced canopy density, with improved visibility of ground-level features. For each campaign, UAV photogrammetry and MLS were performed on the same day to ensure consistent object conditions and facilitate reliable data integration. The acquisition methodology follows established procedures from previous research (Perfetti et al., 2023). Together, these datasets support comparative analysis across distinct temporal states, enabling the investigation of both seasonal variability and longer-term landscape transformation. To ensure comparability, acquisition parameters, including flight configurations, sensor settings, ground control distribution, and MLS trajectory planning, were carefully standardised to maintain consistent spatial resolution and geometric accuracy across epochs. At the same time, differences in vegetation density, illumination, and site accessibility provide an opportunity to evaluate the performance of the sensing techniques under varying environmental conditions.

3.1.3 Management and Botanical Data: In addition to the multi-temporal survey data, auxiliary datasets provided by local management authorities were incorporated to support interpretation and validation. These include an inventory of key garden elements with annotated imagery showing their spatial distribution, a detailed botanical survey describing species, distribution, and condition, and technical documentation of site infrastructure, including electrical and mechanical plans. Provided in PDF and DWG formats, these materials supply complementary semantic and operational information not captured through 3D surveying, enabling a more comprehensive understanding of the site. They also serve as independent references for validating detected changes, including vegetation growth or loss, maintenance interventions, and functional modifications. Their integration enhances the reliability of the multi-temporal analysis and supports its application in conservation and management, while contributing to a more complete 3D, even 4D documentation of the garden.

3.2 Multi-Sensor Survey Workflow

3.2.1 UAV Photogrammetry: UAV-based photogrammetry was employed as the primary method for large-scale spatial data acquisition, complementing ground-based surveys and ensuring complete coverage of the study area. A DJI Phantom 4 Pro v2 platform equipped with a 20 MP RGB camera was used to acquire 606 images in 2023 and 760 images in 2025 through an automated grid flight at an altitude of 50 m above ground level, achieving centimetre-level ground sampling distance (GSD). Image acquisition followed a nadir-oriented configuration with high forward and side overlap (>80% and >70%), enabling robust feature matching and dense point cloud generation (Perfetti et al., 2023). Both surveys were constrained to the same GNSS-measured GCPs, ensuring consistent georeferencing and facilitating integration across datasets. Image processing was conducted using an SfM and Multi-View Stereo (MVS) workflow, including feature detection and matching, bundle adjustment, and dense reconstruction, producing a georeferenced point cloud, DSM, and orthophoto.

3.2.2 Mobile Laser Scanning: MLS was employed to complement UAV photogrammetry by addressing its limitations in vegetation-rich environments, particularly occlusion and insufficient ground penetration beneath dense canopies. Data acquisition was carried out using a Heron MS Twin Colour system (Gexcel srl), integrating dual LiDAR sensors within a SLAM-based positioning framework, enabling direct range measurements independent of surface texture and illumination. Surveys were conducted along multiple trajectories covering the main pathways and accessible areas of the garden, ensuring sufficient spatial redundancy and overlap. In 2023, three trajectories were completed in approximately 30 minutes, while in 2025, four trajectories were acquired in approximately 40 minutes. The additional trajectory (blue) in 2025 was introduced to capture areas affected by recent maintenance interventions and to improve overall coverage (Figure 2). The SLAM algorithm estimates sensor trajectories by continuously registering successive scans, with loop-closure constraints applied to reduce cumulative drift. However, such systems remain sensitive to trajectory geometry and environmental conditions, potentially introducing local distortions in areas with repetitive structures or limited features. To mitigate these effects, acquisition followed closed-loop configurations, and processing included trajectory optimisation, loop-closure correction, and noise filtering, resulting in a point cloud generated within a consistent reference frame. The detailed processing workflow follows the methodology previously described (Perfetti et al., 2023).

3.2.3 Multi-Sensor Data Integration: UAV photogrammetric and MLS datasets were integrated within a unified spatial reference framework, using the UAV-derived model as the primary georeferenced reference (Figure 3). The UAV dataset was processed and georeferenced in the WGS84 /

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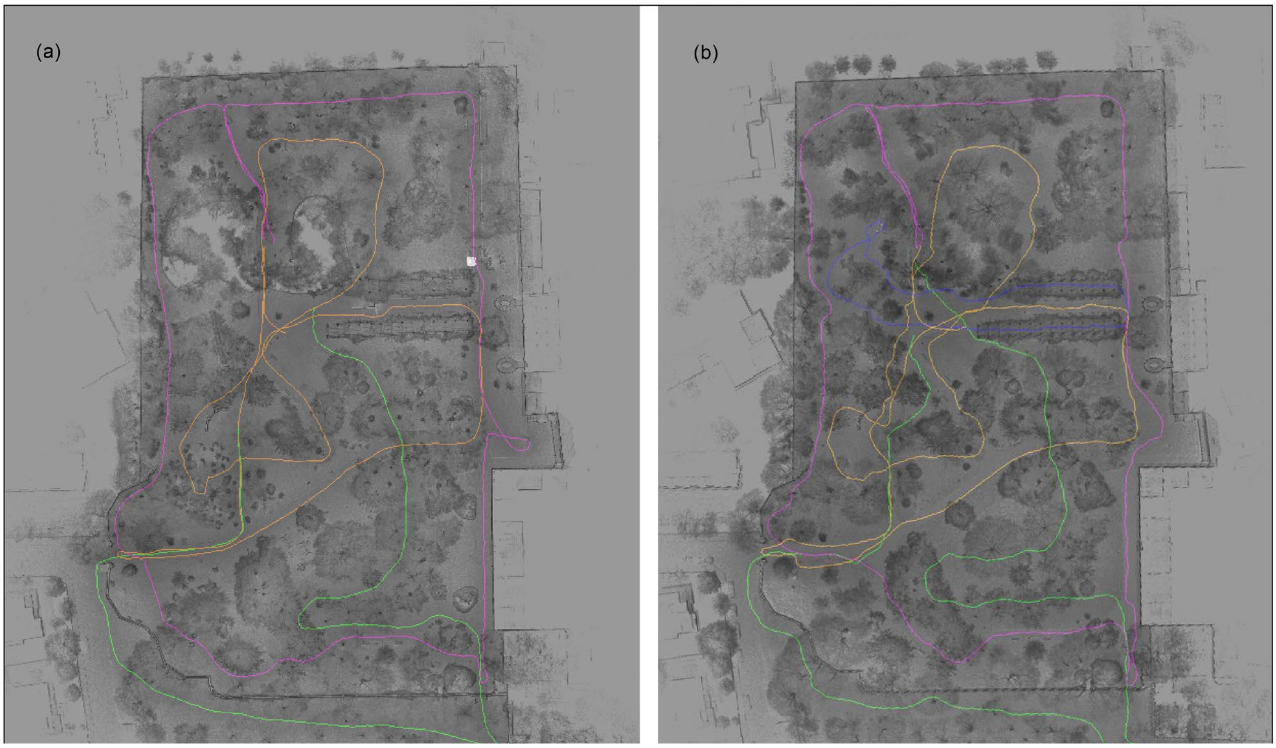

Figure 2. MLS trajectories with blueprints for the two survey campaigns: 2023 (a) and 2025 (b).

UTM Zone 32N coordinate system using a network of GCPs, ensuring centimetre-level absolute accuracy and minimising global deformation. This dataset subsequently served as the reference for MLS integration. The acquired MLS data were processed in Heron Desktop, where SLAM-based trajectory estimation and loop-closure optimisation ensured internal consistency. The MLS point cloud was then aligned to the UAV dataset using a combination of target-based and cloud-based registration, constrained by GCPs and overlapping geometric features within the same coordinate framework. Given differences in acquisition geometry and point distribution, residual alignment errors were carefully evaluated in overlapping areas, particularly along pathways and open spaces where both datasets are more reliable. The integration strategy preserved the complementary characteristics of the datasets, high-density, surface-oriented UAV data, and geometry-driven MLS measurements with strong under-canopy representation. Quantitative consistency was assessed using control-point comparisons and local cloud-to-cloud distances, confirming that residual discrepancies remained within acceptable tolerances for subsequent analysis.

3.3 Multi-Temporal Analysis Method

3.3.1 Temporal Harmonisation: Multi-temporal analysis requires controlling differences arising from temporal variability rather than geometry alone. Building on the multi-sensor integration, temporal harmonisation was performed within a unified coordinate framework to ensure comparability between epochs. Given the influence of vegetation dynamics

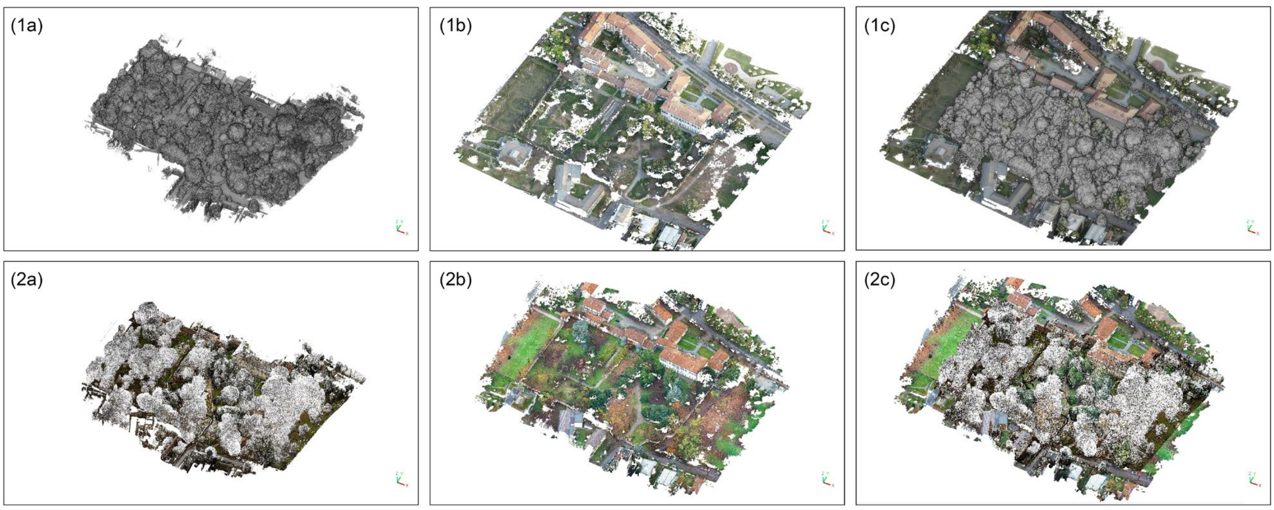

Figure 3. Multi-sensor data integration: Point clouds from MLS in 2023 (1a) and 2025 (2a), point clouds from UAV photogrammetry in 2023 (1b) and 2025 (2b), and integrated point clouds in 2023 (1c) and 2025 (2c).

and acquisition conditions, preprocessing was applied to reduce variability in point distribution and visibility. This included noise filtering and controlled sub-sampling to a uniform resolution of 5 cm, ensuring comparable point density in overlapping areas and minimising bias between UAV and MLS datasets (Figure 4). Stable, non-vegetated surfaces, such as pathways and open ground, were used as reference zones to evaluate local consistency and define acceptable variation thresholds. Particular attention was given to areas affected by occlusion or seasonal differences in vegetation, where variations in point presence may not reflect actual geometric change. The approach preserves meaningful structural differences while minimising artefacts related to acquisition conditions.

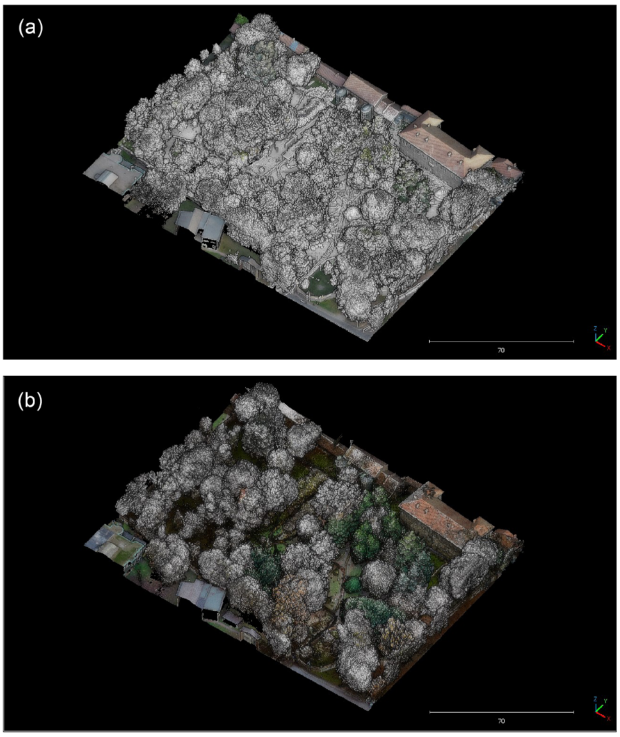

Figure 4. Temporally harmonised integrated point clouds: 2023 (a) and 2025 (b).

3.3.2 Point Cloud Comparison: Following temporal harmonisation, multi-temporal analysis was conducted through direct point-cloud comparison to quantify spatial changes while preserving local 3D structure. C2C distances computation was first applied to obtain a global measure of geometric deviation without requiring surface interpolation, enabling efficient assessment across the entire dataset. To improve robustness in areas with complex geometry and heterogeneous point density, the M3C2 method was implemented to compute distances along locally estimated surface normals, providing scale-adaptive measurements suited for non-planar and vegetation-rich environments. To ensure reliable interpretation, analysis was restricted to zones with sufficient point support, and distance thresholds were defined based on baseline variability observed in stable reference areas, as mentioned earlier, thereby separating significant changes from noise and residual uncertainties. In addition to geometric distances, auxiliary indicators such as local point density variation and vertical distribution were examined to support the interpretation of vegetation-related changes, particularly where partial occlusion or seasonal differences affect point presence. This combined approach enables the identification of both structural and surface-level changes while reducing sensitivity to sampling inconsistencies.

3.3.3 Garden Feature Analysis: Beyond geometric comparison, the multi-temporal point cloud datasets were analysed to identify and quantify changes in key garden elements, including vegetation, terrain, water features, and artificial structures. Vegetation change was assessed by deriving a Canopy Height Model (CHM) and local height differencing, enabling detection of canopy height variations associated with growth, pruning, or removal. To account for differences in sampling and partial occlusion, local point density and vertical distribution metrics were used to support the interpretation of vegetation-related changes. Terrain variation was analysed using ground-filtered point clouds and elevation differencing, enabling the detection of subtle surface modifications, particularly along pathways and open areas. Hydrological features, such as the internal watercourse, were extracted using elevation-based segmentation and surface continuity analysis, enabling identification of changes in water extent and flow conditions. Artificial elements, including pathways, edges, and built structures, were examined both as stable references for validation and as dynamic components affected by maintenance interventions such as resurfacing, repair, or spatial reconfiguration. Quantitative metrics were derived directly from point cloud analysis, including M3C2 comparison, CHM-based differencing, and elevation analysis. CHM and elevation differences were represented as raster surfaces and analysed in QGIS, which served as a complementary environment for delineating regions of interest, organising thematic layers, and relating detected changes to garden features, botanical surveys, and management records, thereby supporting interpretation and management.

4. Results and Validation

All quantitative results were derived from point cloud–based analysis, while GIS operations were limited to spatial referencing, region definition, and contextual interpretation. The performance of the proposed multi-sensor, multi-temporal workflow was evaluated through quantitative metrics aligned with key methodological stages, including data integration, temporal harmonisation, and feature-based change analysis.
These metrics assess geometric accuracy, spatial completeness, and sensitivity to change detection. The first two are based on the 2023 dataset, in which denser vegetation coverage provides a more rigorous test of integration performance (Table 1).

Criterion	Metric	Value
Geometric Accuracy	RMSE (UAV)	2.3 cm
	RMSE (Integrated)	2.5 cm
	Residual deviation	±2 cm
Spatial Completeness	UAV density	2380–5169 pts/m^2
	MLS density	4686–7518 pts/m^2
	Ground coverage (UAV)	60–65%
	Ground coverage (Integrated)	>90%
Change Detection	Threshold	±2 cm
	Canopy change	0.5–1.2 m
	Tree removal	>4.5 m
	Terrain change	5–10 cm
	Water level change	20–30 cm

Table 1. Evaluation metrics of results from the multi-sensor, multi-temporal workflow.

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Geometric accuracy was assessed using GCPs and stable reference surfaces. The UAV-derived dataset achieved an RMSE of approximately 2.3 cm. In comparison, the integrated UAV–MLS dataset showed an RMSE of 2.5 cm, reflecting a minor additional uncertainty introduced by SLAM-based MLS processing. Residual deviations in stable areas remained within ±2 cm, which presents cloud-to-cloud distance distributions over non-vegetated zones. These values are consistent with reported accuracies in comparable multi-sensor studies (2–5 cm), confirming that the integration process provides sufficient geometric reliability for multi-temporal analysis.

Spatial completeness was evaluated through point density distribution and effective ground coverage. UAV photogrammetry produced relatively uniform point densities of 2380–5169 points/m² in open areas but showed a significant reduction under dense canopy, where occlusion rates exceeded 60%. In contrast, MLS data achieved densities of 4686 –7518 points/m² along survey trajectories, substantially improving the representation of ground surfaces and vertical structures. The integrated dataset demonstrates a clear improvement in completeness, with effective ground coverage increasing from approximately 60–65% (UAV only) to over 90%, as summarised in Table 1. This confirms the measurable benefit of multi-sensor integration in vegetation-rich environments.

For change detection results (Figure 5), a significance threshold of ±2 cm was defined based on baseline variability observed in stable, non-vegetated reference areas. C2C distances computed within these regions exhibited a standard deviation (σ) of approximately 1 cm. Following established practices in multi-temporal point cloud analysis, a $\pm 2\sigma$ threshold was adopted to distinguish meaningful geometric changes from residual noise and registration uncertainty. Through the M3C2 algorithm, vegetation analysis shows canopy height differences ranging from 0.5 m to 1.2 m, as well as a clear tree removal event with vertical differences exceeding 4.5 m. Terrain changes of approximately 5–10 cm were detected along pathways, while the internal watercourse showed a 20–30 cm reduction in elevation, indicating altered hydrological conditions. The locations of the samples for the M3C2 methods are shown in Figure 6. And CHM and elevation differences were analysed in QGIS to represent the overall temporal change for documentation and subsequent management actions (Figure 6). Additionally, point density analysis identified localised reductions of up to 40%, corresponding to pruning or vegetation thinning, though seasonal change could also be a factor. These results demonstrate that the workflow is sensitive to both major structural changes and more subtle variations in vegetation dynamics.

The reliability of detected changes was validated using independent botanical surveys and maintenance records. Consistent with Table 1, validation results indicate a high degree of correspondence between detected changes and the reference data. Tree removal events, characterised by significant vertical differences and the absence of local points, were directly confirmed by maintenance records and annotated inventories. Areas of reduced canopy height and density align with documented pruning and vegetation management activities. Terrain modifications along pathways correspond to recorded

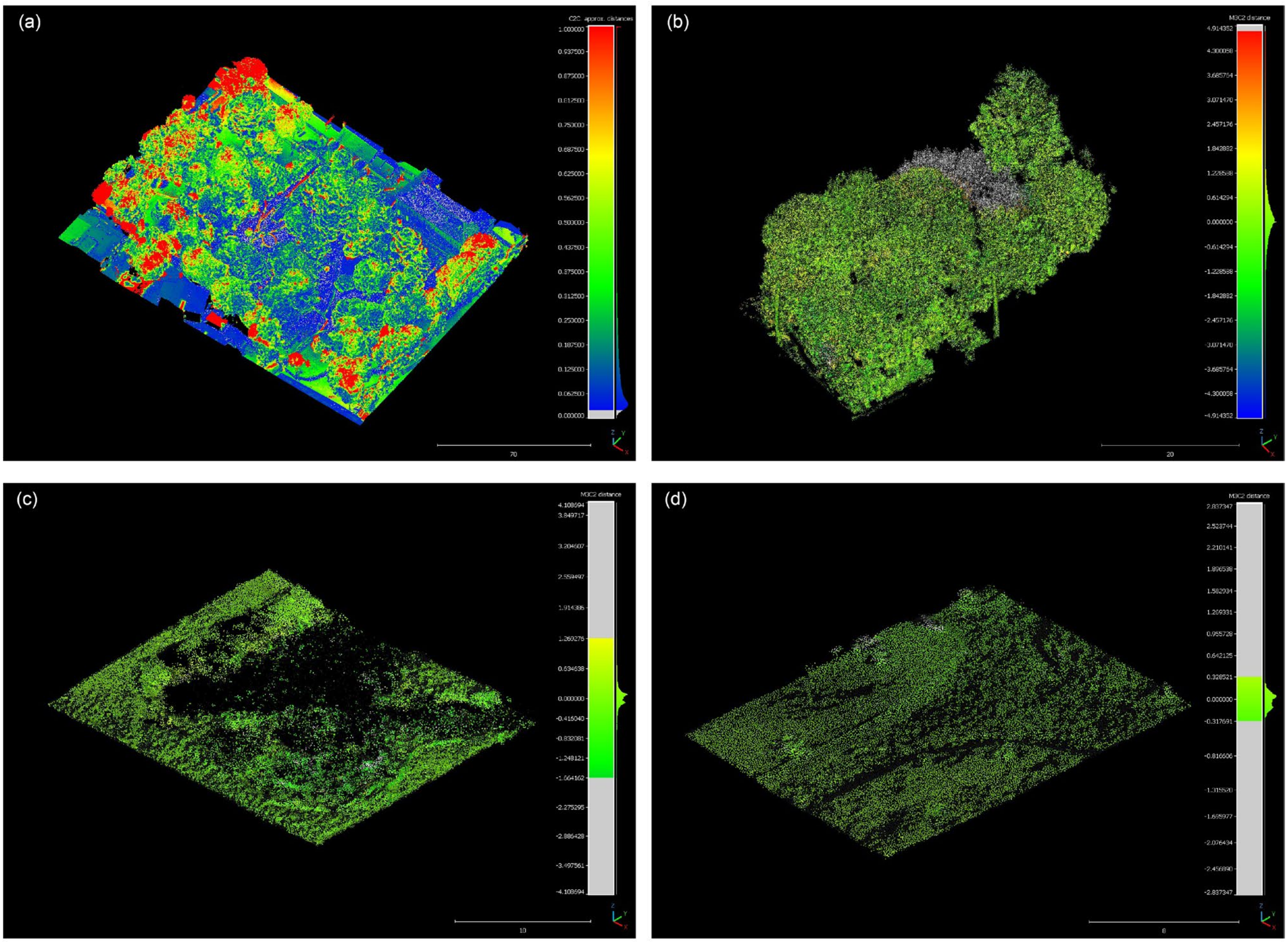

Figure 5. Multi-temporal change detection based on point cloud comparison in 2023 and 2025. C2C distances for global deviation (a); M3C2 for detailed analysis: canopy change and tree removal (b), water level change (c), and terrain change (d).

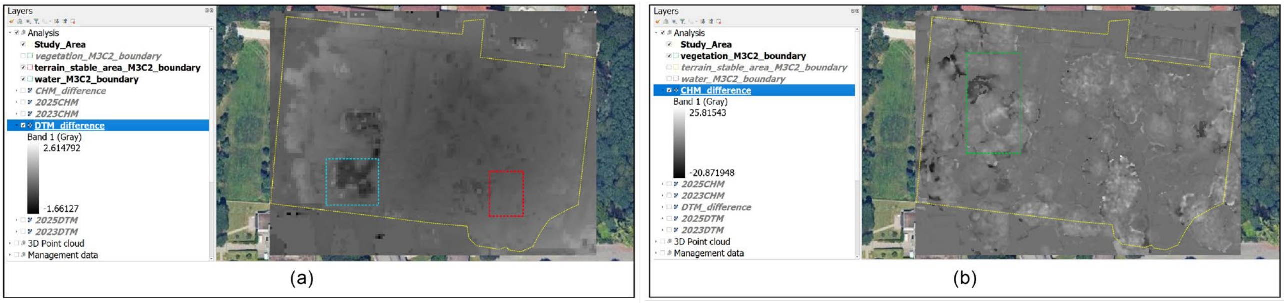

Figure 6. Feature-level interpretation of detected changes using GIS-based analysis: DTM difference (a) and CHM difference (b).

maintenance interventions, while changes in the internal watercourse are consistent with site condition reports and hydrological observations. All 3D datasets were further integrated into QGIS for comprehensive spatial analysis, where they were combined with management materials and historical documents to support subsequent interpretation, management, and monitoring (Figure 7).

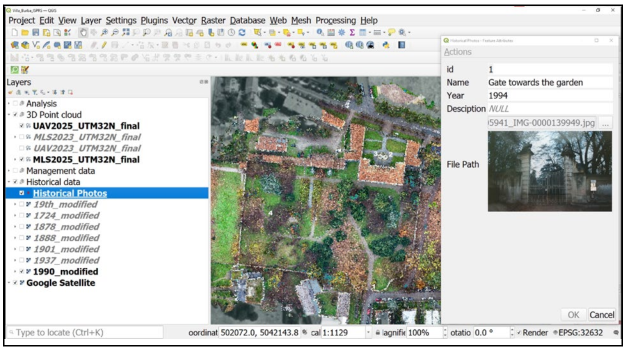

Figure 7. Multi-source management in QGIS.

5. Web-Based Visualisation Platform

To support efficient access and practical use of the generated datasets, the integrated multi-sensor and multi-temporal point clouds were deployed within a web-based 3D environment using a Cesium-based framework. The fused UAV–MLS datasets from each survey epoch were first converted into the 3D Tiles format, enabling structured streaming of large-scale point clouds while preserving spatial reference and hierarchical organisation. The implementation was designed to support direct comparison of heterogeneous datasets rather than generic visualisation. Multi-source point clouds (UAV and MLS) were unified within each epoch, while multi-temporal datasets (2023 and 2025) were linked through an interactive timeline interface (Figure 8). This allows users to scroll through time and dynamically explore changes between epochs, facilitating intuitive assessment of spatial differences in areas without additional preprocessing or external software.

The platform was further configured to support practical inspection and interpretation of landscape changes identified in the analysis. By enabling direct navigation within the georeferenced point cloud environment, users can visually verify detected changes within their real spatial context. This is particularly relevant for historic garden management, where both natural dynamics and maintenance interventions should be interpreted in relation to surrounding conditions. In addition, the use of a web-based framework facilitates access for non-technical stakeholders, enabling exploration of multi-temporal datasets without specialised tools. In this way, the platform functions not only as a visualisation interface but as an operational layer linking multi-source 3D data with analysis results, supporting validation, communication, and long-term documentation of landscape transformation.

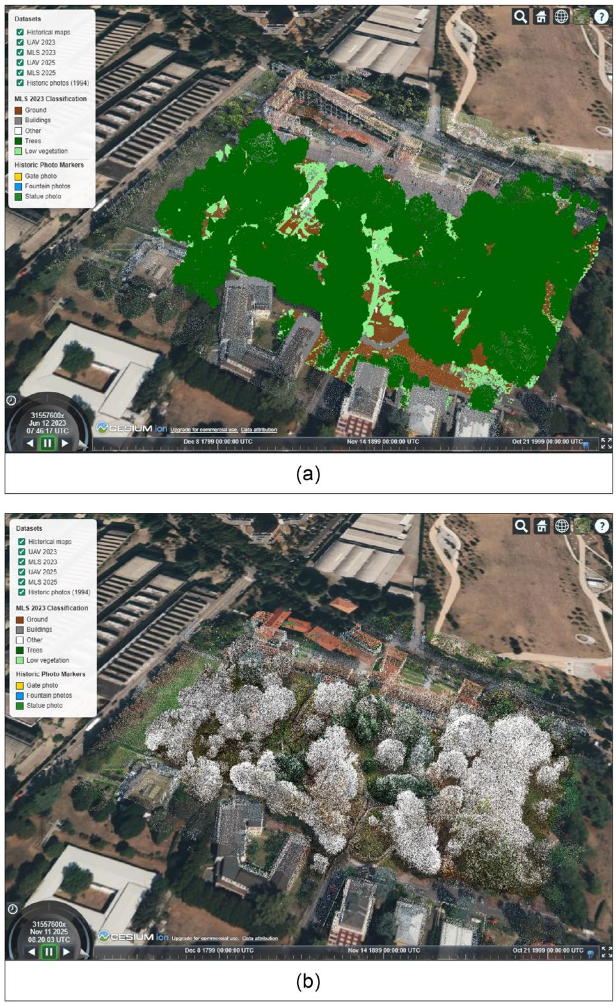

Figure 8. Web-based interaction of multi-sensor and multi-temporal point cloud data using the Cesium platform: 2023 (a) and 2025 (b).

6. Discussion

The results confirm that the proposed multi-sensor and multi-temporal workflow effectively improves the documentation of historic gardens. However, its significance lies less in technical integration alone and more in how it addresses the inherent complexity of these environments. While UAV and MLS data clearly complement each other in spatial coverage, their integration also introduces methodological dependencies, particularly related to sampling heterogeneity and sensor bias. The observed improvement in completeness should therefore not be interpreted as a purely additive effect, but as the result of balancing different data characteristics. In this sense, the workflow demonstrates that reliable representation in vegetation-rich heritage contexts depends not solely on increasing data volume but on carefully managing interactions among acquisition methods, environmental conditions, and analytical objectives.

A critical aspect emerging from this study is the role of temporal consistency, which remains insufficiently addressed in many existing approaches. Although multi-temporal datasets are increasingly available, their comparability is often assumed rather than rigorously evaluated. The results show that even moderate variations in vegetation conditions can significantly influence point distribution and visibility, affecting both data quality and interpretation. This suggests that temporal variability should not be just treated as a source of uncertainty, but as an intrinsic characteristic of living landscapes that should be explicitly incorporated into the methodological design. In this context, the selection of acquisition timing is a strategic decision that influences not only data completeness but also the reliability of detected changes.

The integration of quantitative evaluation with external validation improves the robustness and interpretability of the workflow, but it also reveals limitations in current validation practices. Although agreement with botanical surveys and maintenance records supports the reliability of detected changes, this process remains dependent on the availability and quality of external data. In many heritage contexts, these records may be incomplete, inconsistent, or unavailable, limiting the transferability of this approach. This highlights the need for more systematic validation frameworks that can operate independently of auxiliary datasets, or for methodologies that explicitly account for uncertainty when such data are lacking.

Despite improvements from multi-sensor integration, occlusion effects and complex vegetation structures continue to limit data completeness, particularly in dense or layered environments where neither photogrammetry nor MLS can fully capture all spatial components. In addition, differences in point density and acquisition geometry introduce non-uniform sampling, which may influence both feature extraction and change detection. Although harmonisation strategies can reduce these effects, they cannot eliminate them, and residual biases may still affect quantitative results. Furthermore, temporal comparison remains sensitive to non-structural factors such as seasonal variation, illumination, and environmental conditions, complicating the distinction between transient and permanent changes.

From a broader methodological perspective, the study demonstrates that the value of multi-temporal 3D data lies not only in detecting change but in enabling its interpretation within a wider landscape context. Relating geometric differences to ecological processes and management interventions represents a shift from descriptive documentation to analytical understanding. However, this interpretative step is not fully automated and still relies on expert knowledge and contextual information. While quantitative methods can identify where changes occur, understanding why they occur remains partially dependent on domain-specific expertise.

The implementation of a web-based visualisation environment highlights both opportunities and limitations in translating geomatics workflows into operational tools. While the platform improves accessibility and facilitates exploration of multi-temporal datasets, its functionality remains largely focused on visualisation and manual interpretation. The absence of integrated analytical tools limits its capacity to support fully data-driven decision-making. This suggests that future developments should focus not only on improving data accessibility but also on embedding analytical capabilities and uncertainty assessment within web-based environments. Such integration would enable more effective use of multi-source, multi-temporal data in long-term monitoring, thereby supporting adaptive management of historic gardens as dynamic, evolving heritage systems.

7. Conclusions

This study proposes a multi-sensor, multi-temporal geomatics framework to document and analyse historic gardens as dynamic cultural landscapes. By integrating UAV photogrammetry with MLS, the approach achieves centimetre-level geometric accuracy and significantly improves spatial completeness, particularly in vegetation-rich environments where single-sensor methods are insufficient. More importantly, the results demonstrate that temporally consistent 3D datasets enable reliable detection and quantification of landscape transformations, including changes in vegetation structure, terrain, and water features. This shifts the application of geometry in this field from static documentation toward process-oriented interpretation. The findings also highlight the importance of integrating quantitative 3D data with contextual information, such as botanical surveys and management records, to distinguish between natural processes and human interventions. The deployment of multi-temporal datasets within a web-based 3D environment enhances accessibility and supports long-term reuse, but also reveals the need for more integrated analytical capabilities. In summary, the proposed framework provides a transferable and evidence-based approach for monitoring and managing historic gardens as evolving systems, contributing to a broader shift in heritage studies from recording spatial conditions to understanding and supporting their continuous transformation.

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