Exploring 4D Representation of Historic Gardens: A Semantic and Multi-Source Integration Framework Using GIS and Cesium Platforms

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Abstract

Historic gardens are living forms of Cultural Heritage whose spatial identity is inseparable from continuous processes of growth, decay, and maintenance. Although recent advances in laser scanning, photogrammetry, and mobile mapping systems enable highly accurate three-dimensional documentation, most digital models remain limited to static representations. The temporal dimension, essential for understanding and managing garden heritage, is rarely integrated as an intrinsic component of spatial data.
This paper explores an experimental four-dimensional integration framework for historic gardens that combines point cloud data, semantic and multi-source data fusion based on GIS, and web-based 4D visualization. Rather than aiming at a complete temporal reconstruction, the approach investigates how a single-epoch 3D survey can act as a temporal anchor for integrating historical documentation and future-oriented scenarios within a unified spatial environment. The framework is tested on the historic garden of Villa Burba (Rho, Milan, Italy). Using open-source tools, point clouds from mobile laser scanning are processed using machine learning and semantically structured in a GIS environment, where time is modelled as a relational property describing transformation processes. The integrated model is visualized in the Cesium web platform, enabling interactive exploration of spatial-temporal relationships. The results demonstrate the feasibility of a scalable and interpretable 4D framework for living landscape heritage.

1. Introduction

Digital documentation technologies have become fundamental tools in the study and management of Cultural Heritage (CH). The progressive maturation of laser scanning, close-range and aerial photogrammetry, and, more recently, mobile mapping techniques has enabled the systematic acquisition of architectural and landscape environments with high geometric accuracy and spatial completeness. These developments have significantly advanced the digital representation of built heritage, supporting analytical workflows, conservation planning, and visualization. However, when applied to landscape architecture, particularly to historic gardens and designed landscapes, the prevailing emphasis on geometry reveals important conceptual and methodological limitations.
Historic gardens constitute a distinct and complex category of CH. Unlike architectural monuments, they are not defined by stable material configurations, but by the continuous interaction among designed spatial structures, vegetation, ecological processes, and long-term maintenance practices. Their form is incrementally shaped through cycles of growth, decay, seasonal variation, and human intervention, resulting in landscapes that evolve rather than persist unchanged (Harney, 2014). Consequently, the significance of historic gardens is inseparable from time, which exists not as an external attribute but as an intrinsic dimension of their spatial identity.
Despite the increasing availability of high-resolution three-dimensional (3D) survey data, most digital representations of historic gardens remain temporally constrained. Point clouds and surface models typically capture a single state of the landscape, providing precise but static descriptions of environments that are inherently dynamic. While these models effectively record spatial configurations, the data, when put to use, have already become references to a past point in time, limiting their capacity to depict long-term patterns of transformation. Existing approaches to four-dimensional (4D) heritage modelling have predominantly focused on architectural contexts, where temporal change is reconstructed through successive surveys or formalized within Building Information Modeling (BIM) frameworks (Sedek et al., 2024; Vassena et al., 2023). These strategies are less applicable to historic gardens and other types of landscape architecture, where change is continuous, cumulative, and often only partially documented.
The core challenge in extending digital garden documentation toward a 4D perspective lies not only in the scarcity of multi-temporal datasets but in the absence of data models capable of representing time as a meaningful component of spatial information. In existing workflows, temporal information is reduced to chronological labels or external metadata, disconnected from the geometric and semantic structure of the model (Kokla and Guilbert, 2020). Such representations are insufficient for supporting interpretation, analysis, and management in landscape heritage contexts, where understanding processes of change is essential.
Therefore, this paper proposes a 4D integration framework to face this limitation. Using the historic garden of Villa Burba in Italy as a case study, the approach demonstrates how point cloud data derived from 3D surveys, historical documentation, and future-oriented information can be semantically integrated within a GIS environment and visualized through a web-based platform, thereby supporting temporally informed interpretation of living heritage landscapes.

2. Background and Related Work

2.1 4D Documentation in Cultural Heritage

In CH research, 4D documentation has evolved through multi-epoch data acquisition and phase-based reconstruction within architectural contexts. Successive 3D survey campaigns are commonly used to observe deformation, material deterioration, and structural evolution over time, particularly in masonry

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structures, bridges, and towers, where these changes can be quantified through well-defined temporal intervals (Di Lenardo et al., 2025; Hu et al., 2025; Zhu et al., 2025). Additionally, BIM and Historic Building Information Modeling (HBIM) environments have been utilized to formalize temporal information by associating geometric elements with construction phases, restoration campaigns, or historical stratigraphy (Hu et al., 2025). In these contexts, time is typically modelled as a sequence of discrete states linked to documented events, enabling explicit temporal queries and comparisons.

The effectiveness of this paradigm is closely tied to the characteristics of architectural change. Buildings and monuments typically undergo episodic, event-driven transformations, which are well documented in archival sources such as construction records, maintenance logs, and restoration reports. Consequently, temporal boundaries can be clearly delineated and systematically encoded within 4D models. However, as several studies have noted, this event-based conception of time becomes problematic when extended to garden and other landscape heritage, where change is continuous, seasonal, and non-linear (Hearn and Fagerholm, 2025; Li et al., 2025a).

In historic gardens and designed landscapes, geometric variation is primarily shaped by continuous and cyclical processes such as vegetation growth, seasonal change, pruning, and routine maintenance. Multi-temporal surveys reveal that differences between datasets reflect short-term ecological dynamics rather than long-term structural transformations (Li et al., 2025b). When interpreted through discrete, phase-based 4D frameworks, such variations risk oversimplification or misrepresentation. Moreover, the evidence available for landscape change is frequently fragmentary, qualitative, or indirect, further complicating the reconstruction of clearly bounded temporal states.

2.2 Digital Representation of Historic Gardens and Landscapes

The digital representation of historic gardens and designed landscapes has increasingly attracted attention within CH research, particularly as landscape heritage is now understood as a complex system combining architectural, ecological, and social dimensions. Early digital approaches focused on two-dimensional (2D) cartography and landscape analysis based on Geographic Information System (GIS), emphasizing spatial distribution, land-use patterns, and historical evolution through map comparison (Cazzani et al., 2019). Although effective for territorial-scale studies, these representations provided limited insight into the 3D structure of gardens and their spatial experience.

With the advancement of 3D survey technologies, recent studies have demonstrated the value of point cloud data for capturing both built features and vegetation structures, enabling applications such as vegetation classification, canopy analysis, and visibility assessment (Peng et al., 2024; Perfetti et al., 2023). These developments have substantially enhanced the geometric documentation and spatial analysis of historic gardens. However, most implementations remain centred on present-state representation, with relatively limited integration of historical interpretation or temporal modelling.

Several authors have highlighted that historic gardens differ from architectural heritage in both data structure and interpretive needs. Unlike buildings, where geometry corresponds to discrete construction phases, garden landscapes evolve through gradual, overlapping processes that are rarely documented with metric precision (Li et al., 2025a). Historical sources for gardens, such as paintings, engravings, textual descriptions, and maintenance records, are typically qualitative, fragmented, and spatially ambiguous (Ross, 1998). As a result, digital reconstructions of past garden states rely on interpretive hypotheses rather than verifiable geometric evidence.

Existing digital models of historic gardens, therefore, tend to separate 3D survey data from historical knowledge. While some studies integrate archival material as supplementary visualization layers or narrative content, these sources are rarely embedded within the spatial data structure itself. Temporal information is commonly presented through parallel representations, such as timelines, static overlays, or comparative views, rather than encoded as relationships within the model. This separation limits the ability to perform integrated spatial–temporal analysis and constrains the use of digital models for conservation-oriented decision-making.

2.3 GIS, Semantics, and Web-Based Visualization

GIS has become a fundamental environment for structuring CH information, enabling heterogeneous datasets to be integrated within a shared spatial framework. In the context of historic gardens, GIS facilitates linking geometric data with descriptive attributes, such as botanical classification, maintenance practices, or historical provenance, thereby supporting analyses that rely on both spatial configuration and semantic meaning. Unlike purely geometric modelling environments, GIS allows relationships between features to be explicitly encoded, enabling the landscape to be interpreted not merely as a collection of discrete objects but as a system of interrelated and dynamically interacting components.

Recent research has begun to explore more integrative approaches, combining GIS-based semantics with 3D visualization to enhance the interpretation of landscape heritage (Peng et al., 2024; Redweik et al., 2022). GIS platforms provide mechanisms for linking spatial features with descriptive attributes, provenance, and uncertainty, making them suitable for managing heterogeneous landscape data. However, despite these advances, a coherent framework for integrating point cloud geometry, historical documentation, and temporal semantics in historic garden contexts remains underdeveloped. In particular, a limited number of studies address how present-day 3D data can serve as a structural reference for connecting past configurations with projected future transformations within a single, integrated digital model.

Parallel to developments in GIS, web-based 3D visualization platforms have emerged as powerful tools for disseminating and exploring spatial data. Technologies such as CesiumJS enable the interactive visualization of large-scale datasets through standards including 3D Tiles and the Cesium Markup Language (CZML), supporting real-time rendering, temporal filtering, and user interaction (Barrile et al., 2024). These platforms have been adopted in architectural and urban heritage applications, improving accessibility and interpretability for both specialists and broader audiences. Their strengths lie in visualization and interaction rather than analytical modelling, positioning them as complementary environments to GIS-based workflows.

Despite these advances, interoperability between GIS-based semantic models and web-based visualization platforms remains limited. Data exchange involves simplifying geometry and losing semantic richness, particularly when complex attribute structures or temporal relationships are involved. In many cases, web visualizations rely on static exports that disconnect geometry from its underlying semantic logic, reducing the potential for meaningful temporal exploration. This separation is especially problematic for historic gardens, where interpretation depends on understanding relationships between spatial form, historical context, and ongoing transformation. Few studies have systematically explored how this integration can be used to

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represent time as an intrinsic, relational dimension of spatial data, particularly within landscape heritage contexts. As a result, the potential of combining GIS semantics with web-based 3D visualization for 4D representation of historic gardens remains underexplored.

3. Research Gaps and Objectives

Although significant progress has been made in 3D and emerging 4D documentation, current digital heritage workflows remain poorly equipped to represent the temporal logic of historic gardens. Existing 4D approaches, developed primarily for architectural heritage, treat time as a sequence of discrete, well-defined phases reconstructed through multi-epoch surveys, event-based stratigraphy, or HBIM modelling. These methods rest on assumptions of clear temporal boundaries and verifiable geometric states, conditions that are seldom present in living landscapes. Garden transformation unfolds through continuous, overlapping processes, growth, pruning, decay, seasonal change, and routine maintenance, which do not conform to event-based temporal structures. Historical documentation offers little relief. Archival sources are typically descriptive rather than metric, fragmented, and spatially ambiguous. Together, these factors mean that neither available evidence nor existing modelling paradigms can support an integrated representation in which geometry, semantics, and temporality function cohesively. The challenge, therefore, lies not simply in the scarcity of temporal data but in the absence of data models capable of expressing time as an inherent and relational dimension of landscape heritage.

Therefore, this study aims to address this methodological gap by proposing an integrative 4D framework that represents historic gardens as temporally evolving spatial systems, using the present-day point cloud as a temporal anchor to position past configurations and anticipated future trajectories within a coherent spatial–semantic structure. It seeks to embed temporal meaning directly into spatial data through semantic relationships, allowing landscape change to be modelled as a continuous process rather than a series of isolated snapshots. By combining open-source GIS for semantic modelling with CesiumJS for interactive visualization, the study investigates how heterogeneous datasets, 3D survey outputs, archival sources, and conceptual future scenarios can be aligned and explored as a unified temporal system. The main objective is not to reconstruct complete historical stages, but to evaluate the feasibility and interpretive value of a 4D approach that enables historic gardens to be understood, analysed, and managed as evolving spatial entities.

4. Methodology

4.1 Case Study

The historic garden of Villa Burba, located in Rho (Milan, Italy) (Figure 1), provides an appropriate context for evaluating the proposed 4D integration framework. Established in the seventeenth century as a private villa garden following the formal principles of Italian tradition, the site has undergone multiple phases of transformation, reflecting changes in ownership, function, and maintenance practices. During the nineteenth and twentieth centuries, the property transitioned from an aristocratic estate to a publicly managed civic space, leading to notable modifications in its spatial organisation, vegetation structures, and patterns of use. Components of the original design coexist with later additions and adaptive interventions, resulting in a landscape characterised by historical layering and ongoing functional evolution.

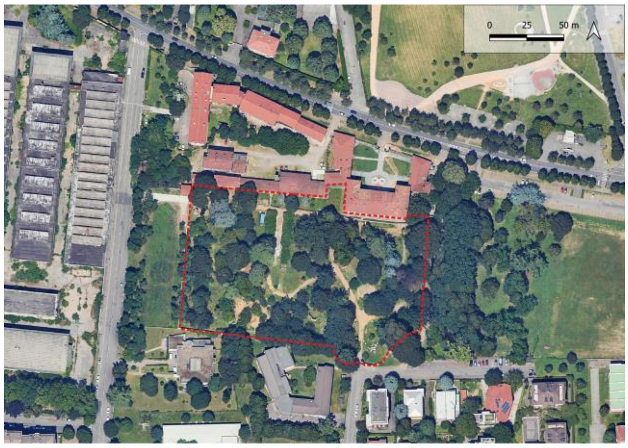

Figure 1. The historic garden of Villa Burba (highlighted within the red dashed boundary).

These documented yet uneven changes make Villa Burba representative of living landscape heritage. Its development illustrates conditions common to many historic gardens, including the partial loss of formal structures, the introduction of new species or circulation routes, and the progressive adaptation of the site to changing social requirements. Contemporary management activities, such as routine pruning, replanting, and periodic redesign, further contribute to its dynamic character.

4.2 Data Sources and Temporal Scope

The methodology integrates three groups of data corresponding to different temporal dimensions (past, present, potential future). These dimensions are not treated as isolated temporal states but as interrelated layers that contribute to a continuous and relational understanding of landscape transformation (Figure 2).

Past data derived from historical sources, including cadastral maps, municipal plans, and early photographic records of Villa Burba. Although these materials lack metrically reliable geometry, they contain essential information on past spatial configurations, planting arrangements, and design intentions. Their spatial ambiguity makes them unsuitable for geometric reconstruction. However, they provide critical semantic evidence for establishing temporal relationships. Within the framework, these sources are incorporated not as reconstructed geometries but as relational attributes that link present-day spatial entities to documented historical states or functions.

Present data are represented by high-density point clouds collected in April 2023. Acquired through mobile laser scanning, the dataset captures both built and vegetated elements with a resolution of approximately 2 cm and without colour information (Perfetti et al., 2023). The level of geometric detail is sufficient to support semantic segmentation and classification. This point cloud serves as the geometric and temporal anchor for the framework, providing a stable spatial reference against which historical evidence and conceptual future scenarios can be aligned. Its accuracy and completeness enable it to function simultaneously as the baseline for semantic enrichment and as the structural reference for temporal modelling.

Future-oriented data consist of conceptual representations of anticipated transformation processes, such as vegetation growth, routine pruning cycles, and planned maintenance interventions. As no predictive datasets exist for the site, these future layers are modelled as parametric or semantic constructs rather than deterministic forecasts. Their purpose is to test how temporal

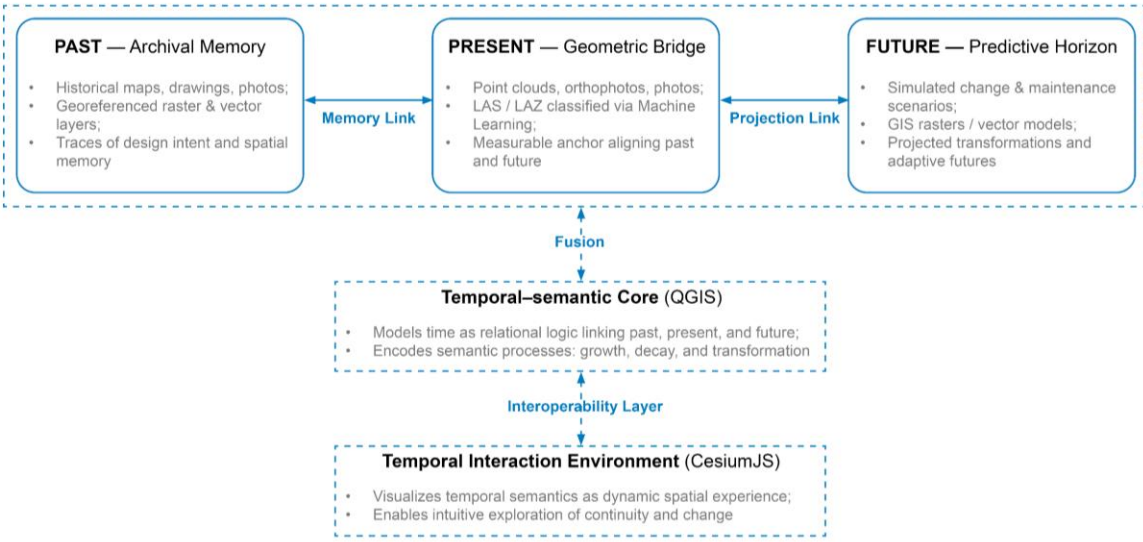

Figure 2. A 4D integration framework for Villa Burba linking multi-temporal data and visualization.

meaning can be encoded within spatial data. In this study, future representations focus primarily on plausible changes to tree structures based on observed seasonal dynamics (e.g., spring, summer, autumn, winter) and long-term management practices (e.g., adding or removing). By expressing these transitions through semantic relationships, the framework establishes a temporal logic that links present geometry to potential future conditions.

All datasets are integrated within a unified spatial reference system (WGS 1984, UTM Zone 32N), providing a consistent geometric foundation for subsequent semantic structuring and temporal modelling.

4.3 Point Cloud Processing and Classification

The mobile mapping survey of Villa Burba produced a dense and heterogeneous point cloud that required a structured processing workflow. A multi-level, multi-resolution (MLMR) machine-learning pipeline was adopted to achieve efficient, robust, and accurate classification across varying point densities and complex vegetative structures (Teruggi et al., 2020; Zhang et al., 2022). Pre-processing involved statistical outlier removal to reduce noise and manual segmentation to eliminate elements outside the study area. Ground and non-ground separation using elevation-based filters generated a clean terrain layer, improving the distinction between vegetative and architectural features.

Following pre-processing, the whole dataset was computed to characterise surface behaviour across the point cloud. Metrics, including anisotropy, planarity, linearity, surface variation, sphericity, and verticality, were calculated in accordance with established multi-scale feature analysis practices for cultural heritage point cloud processing. Together, some descriptors were selected as training samples that captured differences in geometric organisation and spatial continuity, enabling effective discrimination between terrain surfaces, tree trunks, canopy structures, and architectural elements. They constitute the primary feature set used in the subsequent semantic classification stage.

Semantic labelling was performed using a supervised Random Forest (RF) classifier. Training samples were manually annotated in representative portions of the cloud following an iterative multi-resolution approach to account for variations in point density, occlusions, and vegetation complexity. The RF model was trained using the selected suite of geometric descriptors and then used to predict the entire dataset at an operational point resolution of 10 cm. Cross-validation conducted across multiple sectors of the garden showed consistent classification behaviour, indicating that the model generalised reliably despite spatial heterogeneity in vegetative and built structures.

The final labelled dataset was organised into semantically coherent classes: ground, architectural elements (e.g., walls, building facades), other artefacts (e.g., furniture, utilities), tree structures (with identifiable trunk and canopy components), and low vegetation (grass, shrubs, young trees). Local misclassifications were corrected through targeted manual refinement to ensure category consistency. The resulting low-resolution labelled dataset was then interpolated onto the final high-resolution point cloud to produce a complete, semantically attributed point cloud at survey resolution.

This structured classification transforms the MLS point cloud from a purely geometric dataset into an operational set of spatial entities. These semantically defined units serve as the basis for assigning temporal relations in the QGIS temporal–semantic schema, thereby establishing the classified point cloud as the present-state anchor of the broader 4D integration framework.

4.4 Temporal–Semantic Integration in QGIS

Temporal and semantic integration is implemented in QGIS Desktop 3.40.11 (QGIS Development Team, 2024), which serves as the central environment for structuring feature-level data, organising multisource layers, and encoding temporal relationships. In this workflow, point clouds remain the primary geometric representation of the garden, and vectorisation is applied selectively only where it directly supports temporal modelling. Individual trees are extracted as point features by clustering high-vegetation points and deriving attributes such as height and crown diameter from the classified MLS data. These trees' points constitute the only vector-based temporal entities, as their measurable properties enable the definition of potential growth and maintenance scenarios. All other components of the garden, including grounds, low vegetation, and artificial features, are retained as classified point-cloud layers, preserving the spatial fidelity of the original survey.

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Historical materials are incorporated as georeferenced raster layers rather than reconstructed geometries. Cadastral maps, historical plans, and archival photographs are added to QGIS as spatial layers with appropriate transformations, while their inherent spatial uncertainty is maintained. No attempt is made to derive precise historical geometries. Instead, these sources function as interpretive references that can be visually compared with the present-day point cloud. Where relevant, specific historical information is linked to tree points or localised areas of the cloud through attribute fields, allowing clear differentiation between spatially reliable present geometry and historically informative but imprecise evidence.

Temporal meaning is encoded through relational semantic attributes rather than explicit timestamps. Attributes such as “add”, “remove”, “grows_into”, and “maintenance_info” describe how present entities relate to past conditions or conceptual future tendencies. This relational encoding allows for the representation of processes of continuity, change, and anticipated transformation without requiring multi-epoch 3D datasets.

Future-oriented information is integrated through semantic projection. Estimated growth increments or crown-expansion tendencies derived from present tree metrics are stored as conceptual attributes rather than instantiated as new geometries. This enables exploratory analysis of potential vegetation evolution while acknowledging the absence of deterministic simulation data.

The resulting data structure connects past, present, and potential future states within a coherent relational model, establishing the foundation for temporal interaction and visualization in Cesium.

4.5 Web-Based Visualization and Interaction in Cesium

Web-based visualization is implemented using CesiumJS, with Cesium ion providing the environment for generating and hosting 3D Tiles. The classified point cloud from the previous stages is converted into 3D Tiles through Cesium ion’s tiling pipeline to ensure full compatibility with browser-based rendering. Geometry (3D Tiles) and temporal–semantic information (JSON/CZML) are exported separately to maintain a clear and modular data structure.

Semantic and temporal attributes encoded in QGIS, covering entity identifiers, historical references, and future-oriented parameters, are exported as JSON tables and linked to the corresponding 3D Tiles features through unique feature IDs. These attributes are structured in CZML to ensure native compatibility with CesiumJS. During visualization, CesiumJS loads the 3D Tiles dataset and retrieves associated semantic information by matching the feature ID embedded in each tile to its corresponding record in the JSON or CZML file.

User interaction within the web environment is supported through feature-level selection and attribute querying. When a user selects a tree or any point-cloud element, CesiumJS displays the relevant semantic attributes retrieved from the metadata tables. Temporal categories (historical annotations, present conditions, future parameters) are encoded as state attributes within the CZML schema. CesiumJS reads these attributes and enables filtering or toggling through interface controls, allowing users to compare temporal information without generating multiple geometric models.

No additional geometric processing is performed within the web platform. All spatial content derives directly from the MLS point cloud processed in earlier stages. CesiumJS is used exclusively for rendering the 3D Tiles dataset, loading the external semantic metadata, and applying temporal filtering or selection operations defined in the CZML structure.

5. Results

The processed MLS dataset of Villa Burba produced a final point cloud of approximately 71.2 million points (Figure 3). Following classification, which achieved an overall accuracy of around 96%, and subsequent manual refinement, the dataset was organised into five principal classes: ground (12.1 million points), buildings (3.9 million points), other garden structures (62,600 points), trees (47.4 million points), and low vegetation (7.7 million points). The point cloud showed clear separation between ground surfaces, vegetation, decorations, and built structures.

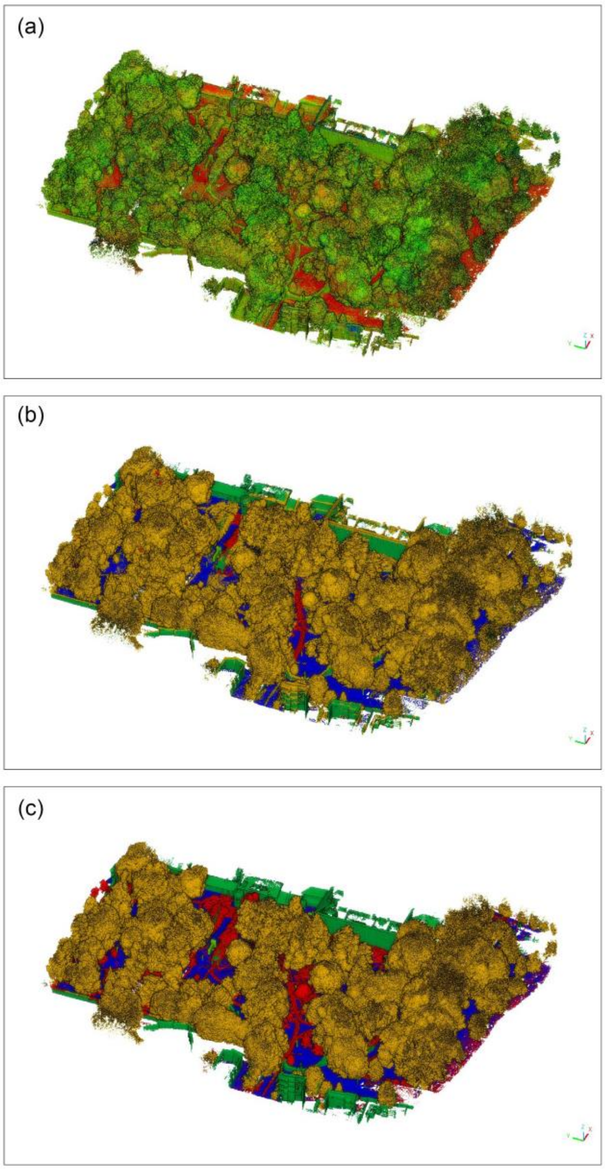

Figure 3. The processed MLS dataset of Villa Burba. Original point cloud acquired at 2cm resolution (a), Random Forest-classified point cloud resampled to 10cm resolution (b), final corrected point cloud at 5cm resolution used for subsequent analysis (c), with five classes: ground (blue), buildings (green), other garden structures (light green), trees (yellow), low vegetation (red).

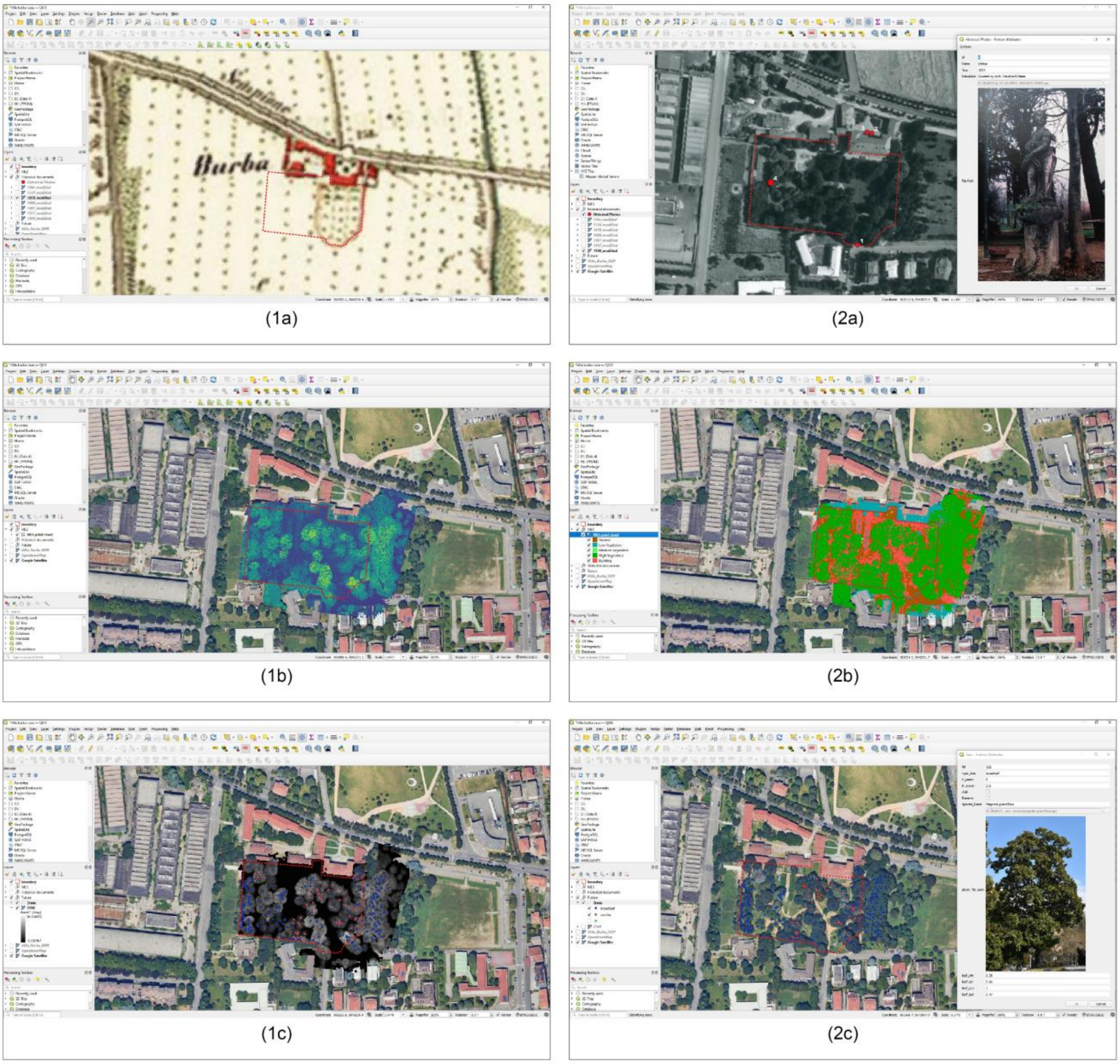

Figure 4. Semantic and multi-source integration in QGIS. Historical maps and archival photographs for contextual visualization (1a, 2a), MLS point cloud data and its Random Forest–based classified visualization (1b, 2b), raster datasets of tree height and canopy extent extracted from the point cloud (1c), and simulations of vegetation dynamics across four seasons together with long-term changes informed by management plan (2c).

All spatial datasets, including the classified point cloud, the extracted tree points, and seven georeferenced historical maps dated 1724-1990, were integrated into a single QGIS project (Figure 4). Historical photos were linked to precise spatial locations through attribute fields. All temporal and semantic attributes associated with the tree points were correctly encoded and fully queryable within the attribute table.

On the Cesium platform, the classified point cloud was visualized as a 3D Tileset with distinct renderings of the five classification categories. All trees' entities were displayed individually, with their height, crown diameter, and semantic attributes accessible through feature selection. Metadata imported from QGIS, including historical references and temporal categories, loaded correctly and could be filtered as separate display states, enabling an integrated 4D visualization of the garden's historical evolution, current condition, and projected seasonal behaviour (Figure 5).

6. Discussion

The results of the Villa Burba case study show that the central challenge of 4D representation in historic gardens is not simply a matter of technological capability. It concerns how knowledge and technical tools are brought together. When change is continuous, uneven and only partially observable, what does it mean to represent that change? Existing approaches often assume that temporality emerges from the accumulation of chronological datasets such as multi-epoch point clouds, repeated photogrammetric surveys or fully reconstructed historical models. The findings presented here suggest that 4D representation can

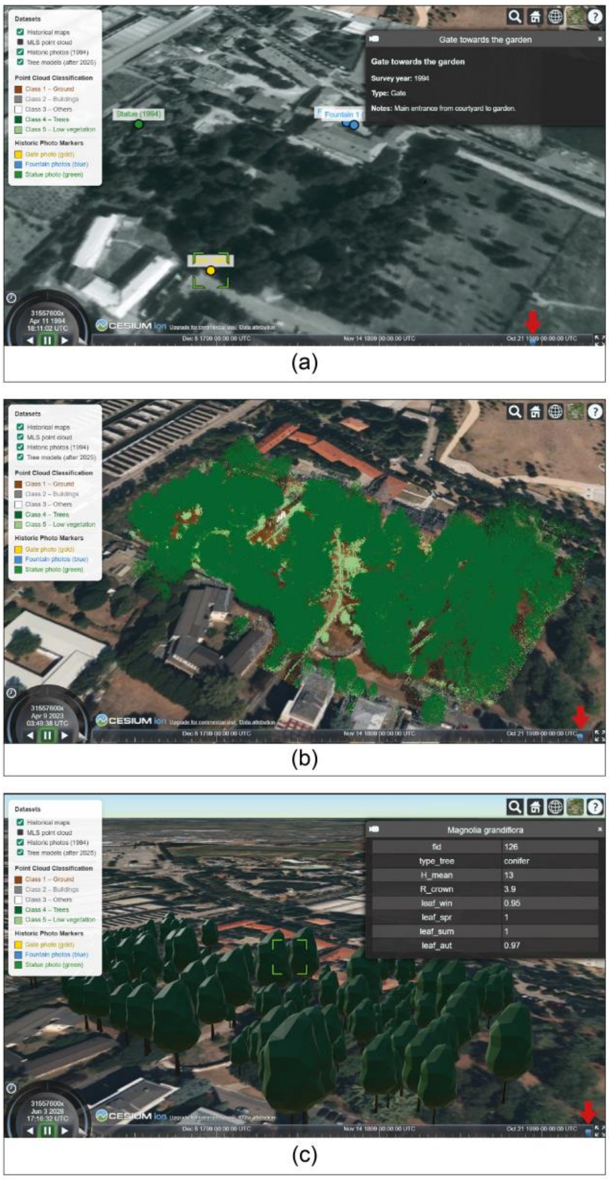

Figure 5. Visualization of multi-source data in Cesium for web-based 4D interaction. Historical datasets (a), the classified MLS point cloud (b), and simulations of future tree changed with attributes describing seasonal canopy variations (c).

follow a different logic. Temporal meaning can be constructed, not only recorded, when spatial entities are embedded within a semantic structure capable of expressing their relationships across time.

Using a single-epoch point cloud as the core temporal reference challenges the common assumption in digital heritage that geometric completeness is a prerequisite for temporal modelling. In many landscape contexts, multi-temporal 3D datasets are unavailable or only partially documented. The Villa Burba results demonstrate that present geometry, once semantically structured, can serve as a reference that connects archival fragments and conceptual future tendencies. This shifts the absence of repeated surveys from a limitation to an opportunity. Time becomes a relational construct rather than a geometric archive. In this perspective, temporal representation in living heritage need not depend on a high level of reconstruction fidelity. It can instead prioritise temporal intelligibility.

The study also highlights the role of GIS in shaping temporal reasoning. GIS is often understood as a platform for storing and organising spatial information. In this work, however, it functions as a semantic engine where temporal logic is authored, examined and revised. QGIS allows temporal states to be represented as structured relational attributes, such as “derived from” or “grows into”, rather than as external descriptive notes. This indicates that temporal modelling in historic gardens may rely less on specialised software and more on rethinking how existing spatial infrastructures are used. GIS becomes an environment for formulating temporal hypotheses, one in which uncertainty, discontinuity, and partial evidence can coexist within a coherent data structure.

The complementary role of CesiumJS reveals a different dimension of the 4D problem. GIS provides the analytical and semantic foundation, while the web environment enables examination of how temporal relationships behave when made interactive. The transfer of information from QGIS to CesiumJS exposes a long-standing tension in digital heritage. Semantic detail is difficult to retain when exporting to visualisation platforms designed for rendering efficiency. The Villa Burba case shows that certain components of temporal meaning survive this translation, for example, state-based filtering and entity-linked metadata, while others are reduced or lost. This suggests that 4D representation requires not only semantic modelling and visualisation but also a clear understanding of how temporal semantics move across platforms and which aspects remain legible to end users.

The limitations identified in this study point to broader structural issues in 4D heritage research. Historical maps and photographs often contain spatial ambiguities that limit their geometric integration. Vegetation attributes derived from the point cloud are simplified estimates and cannot replace ecological models. The absence of multi-epoch survey data prevents geometric verification of temporal transitions. These constraints reflect a fundamental condition of working with living landscape heritage. The temporal record is inherently incomplete. A 4D model of a garden should therefore be understood not as a reconstruction but as a temporal proposition, an organised attempt to express continuity, transformation and potential within the limits of imperfect evidence.

For these reasons, the contribution of the proposed framework lies less in the specific technologies employed and more in the conceptual shift it enables. It demonstrates that 4D representation can emerge through integration rather than accumulation, through semantic organisation rather than complete geometry, and through temporal logic rather than extensive temporal datasets. This reframes the methodological direction for digital garden heritage. Instead of waiting for comprehensive temporal data, researchers can construct relational structures that can absorb new surveys, archival discoveries, ecological simulations, or maintenance records as they become available. In this sense, the framework is not a finished solution. It is a scaffold for ongoing temporal extension, reflecting the condition of the garden itself, which remains open-ended, layered and continually evolving.

7. Conclusion

This study demonstrates that a single-epoch MLS point cloud, when semantically structured and integrated with historical and future-oriented information, can serve as the basis for an exploratory 4D representation of a historic garden. By encoding temporal relationships at the attribute level and organizing heterogeneous datasets within a unified GIS model, the framework enables temporal interpretation without requiring multi-epoch geometric reconstructions. The integration with the Cesium platform further shows that temporal–semantic structures can be maintained in a web-based environment, supporting interactive exploration of spatial entities and their associated temporal states. While the approach does not resolve uncertainties inherent in historical documentation or simplified future projections, it establishes a scalable structure that can incorporate additional temporal data as it becomes available. The framework, therefore, provides a practical and extensible foundation for advancing temporal modelling in living landscape heritage.

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