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High-Resolution LiDAR for Archaeological Prospection in Mediterranean Forested Landscapes: Insights from Two Case Studies in Italy

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Abstract:

This paper presents the results of two high-resolution airborne LiDAR surveys carried out in Mediterranean forested environments with rich archaeological potential. These case studies, located in southern Tuscany and within the presidential estate of Castel Porziano near Rome, illustrate the value of LiDAR-based approaches for identifying and interpreting cultural landscapes that are otherwise obscured by dense vegetation. In the Tuscan case study, which includes the ancient settlement of Roselle and the nearby hill of Moscona, UAV-mounted LiDAR sensors were employed to acquire data over an area of approximately 550 hectares. The resulting point clouds, with an average density of 750 points per square meter, allowed for the detection of subtle topographic features and archaeological structures, including buried walls, road systems, and necropolises. The complexity of the dataset required the development of a multi-stage processing pipeline, combining deep learning techniques and semantic segmentation to differentiate ground surfaces, vegetation, and structural elements, ultimately leading to the creation of detailed Digital Terrain and Feature Models (DTMs and DFMs). Conversely, the Castel Porziano survey covered a large protected area with limited modern disturbance and dense coastal vegetation. While the LiDAR dataset was acquired via manned airborne platforms due to legal and logistical restrictions on drone flights, the results proved equally rich in archaeological information. The high-resolution data enabled a diachronic interpretation of the landscape and revealed patterns of land use, infrastructural networks, and traces of earlier human occupation previously undocumented due to the site's inaccessibility and forest coverage. While the technological setup differed between the two contexts, particularly with regard to drone deployment the central role of high-resolution LiDAR remains consistent. The comparison between these case studies highlights how adaptable and powerful LiDAR technology can be in supporting archaeological research in forested Mediterranean environments. Moreover, the integration of computational techniques such as AI-driven classification and multi-resolution analysis provides scalable solutions for managing large datasets and improving archaeological feature extraction. This contribution emphasizes not only the methodological advancements enabled by LiDAR and AI integration but also the importance of interdisciplinary collaboration between archaeologists, remote sensing specialists, and data scientists. It offers a flexible framework applicable to other Mediterranean contexts where environmental constraints, dense vegetation, and heritage protection pose challenges to traditional archaeological methods.

CCS Concepts

● Lidar → workflow, semantic segmentation; ● landscape archaeology → Roselle (GR), Castel Porziano(RM), Archaeology in Mediterranean maquis;

1. Introduction

In the last decade, the increasing accessibility and performance of UAV-borne LiDAR systems have significantly enhanced archaeological research, particularly in forested and vegetated landscapes where traditional survey techniques face major limitations. The capacity of LiDAR to penetrate dense vegetation and return high-resolution terrain models has made it an indispensable tool for uncovering and interpreting archaeological features hidden beneath the canopy, especially in the Mediterranean context [OPI16; CAM17a; ŠLE2021]. Despite these advancements, challenges remain, especially in the

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development of robust workflows tailored to specific vegetation types, terrain complexity, and seasonal variability characteristic of Mediterranean environments [MGC*22; FON 2024]. This contribution presents a refined and flexible methodology, focusing on the integration of UAV LiDAR data with Artificial Intelligence (AI) techniques for semantic classification and Digital Terrain Model (DTM) generation. Central to this approach is the use of drones and aerial based platforms, which enable high-resolution data acquisition. The proposed workflow addresses the entire analytical pipeline from tailored data acquisition strategies using UAVs, to advanced processing through AI-driven classification, and finally to the archaeological interpretation of the results. Moreover, this work consolidates a replicable and scalable framework that has supported, and in several instances enabled, novel landscape interpretations and the identification of previously undocumented archaeological features across diverse Mediterranean contexts [CMR*25]. Two case studies are central to this reflection: the ancient city of Roselle and the Presidential Estate of Castel Porziano. Both illustrate how a structured AI-driven processing pipeline, rooted in open-source tools and manual annotation can deliver consistent results even in complex and densely vegetated environments [MGC*22; CMR*25]. The aim is to discuss methodological robustness and transferability while acknowledging the specific adaptations required by each context.

2. Case Study: Roselle Complex Archaeology Beneath Vegetation

The archaeological site of Roselle (Rusellae), situated in a hilly, forested landscape in central Italy, provides a challenging, but rewarding, testbed for LiDAR and AI integration. Past work at the site has already underscored the need for high-resolution terrain modeling to support landscape archaeology [Cam2017b; CMR*25]. Here, UAV-acquired LiDAR data and field surveys, have been processed to generate detailed DTMs and identify subtle morphological indicators of anthropogenic activity. The processing workflow unfolds through three main stages.
First, semantic segmentation is performed on the point cloud using a supervised AI model based on a Multi-Level Multi-Resolution (MLMR) framework. This allows for the hierarchical classification of vegetation, ground, and archaeological structures. In a successive moment, filtered ground points are used to produce DTMs, which are then enhanced through visualization methods such as hillshading, openness, and Simplified Local Relief Models (SLRM) [ŠLE2021; MGC*22]. Finally, these visual outputs are interpreted by archaeologist in a GIS environment. This iterative, interdisciplinary process has yielded notable results, enabling the recognition of both known and previously undocumented features such as low-relief wall foundations and ancient road segments masked by vegetation or erosion. However, challenges persist in fine-tuning the classification to distinguish between low shrubbery and anthropogenic traces, a task for which adaptive training sets and contextual field validation remain crucial [MGC*22].

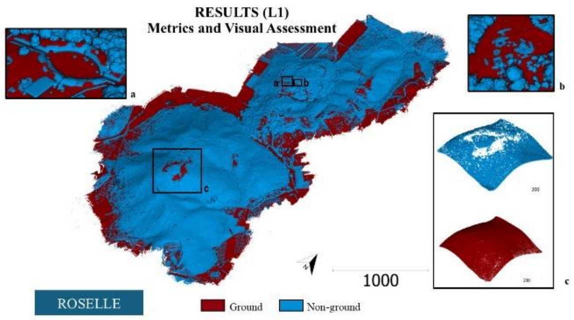

Figure 1: Semantic classification results (Level 1) of the LiDAR point cloud from the Roselle–Moscona case study. Ground points are shown in red, while non-ground points (including vegetation and structural elements) are shown in blue. Insets a and b highlight archaeological features within the Etrusco-Roman settlement of Roselle, including buried walls and infrastructure. Inset c focuses on the summit of the Moscona hill, where there are the remains of a Medieval settlement. This initial classification phase demonstrates how the L1 semantic segmentation removes both vegetation and built structures, enabling the generation of preliminary Digital Terrain Models (DTMs) for further archaeological analysis.

3. Case Study: Castel Porziano. Mapping Environmental and Archaeological Layers

The application of the same methodology in the Presidential Estate of Castel Porziano presents a different scenario. Unlike Roselle, the focus here is on environmental modeling and the paleo-topographic reconstruction of a largely undeveloped, densely forested reserve. The archaeological value of the site lies in its potential to reveal ancient land use patterns and geomorphological alterations linked to past human activity. The high-density point clouds were processed using the same AI-based semantic classification pipeline, enabling effective filtering of vegetation and the extraction of micro-topographic features. Here, too, DTMs were enhanced through visualization techniques, revealing several features suggestive of both natural and anthropogenic origins. The Castel Porziano case study confirms the workflow's adaptability to non-invasive research in protected environments, bridging archaeological and ecological objectives. While no major excavation campaigns are currently planned in the area, the resulting spatial data and models are being integrated into heritage and landscape management frameworks, offering a basis for future research and conservation actions.

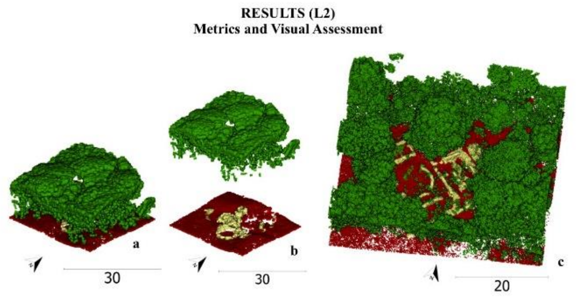

Figure 2: Semantic segmentation results (Level 2) from the Castel Porziano case study. This classification level successfully distinguishes vegetation (green), ground (red), and man-made structures (yellow). Insets a, b and c show close-up views where architectural remains are correctly segmented despite dense canopy cover. These results highlight the enhanced capability of Level 2 classification to reveal hidden structures within complex forested environments.

4. Toward a Transferable and Scalable AI-Driven Workflow

The strength of the proposed methodology lies in its modular and adaptive design. Based entirely on open-source tools such as CloudCompare and QGIS, the workflow allows researchers to process and interpret large LiDAR datasets with limited computational resources and training data. The supervised AI approach requiring modest manual annotation for initial training has proven effective for generalizing across similar terrains, particularly when augmented with small samples from the target site [MGC*22; CMR*25]. The pipeline's hierarchical classification model first distinguishes vegetation from non-vegetation, followed by finer categorization of ground versus structures. This two-step process reflects a growing trend in archaeological remote sensing: the shift from traditional filtering techniques to AI-powered semantic enrichment capable of identifying subtle archaeological markers within complex environmental datasets [FON 2024]. Nevertheless, complete generalization remains elusive. Morphological, ecological and archaeological variability across the Mediterranean still demands site-specific tuning and contextual interpretation. Thus, future developments will aim to enhance automation through deep learning approaches and larger training corpora, with the goal of producing more robust and transferable Digital Feature Models (DFMs) [MGC*22; ŠLE2021].

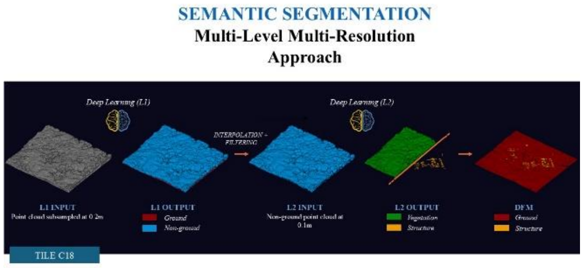

Figure 3: Workflow of the semantic segmentation process applied to a test tile (C18) from the Castel Porziano case study. The first level (L1) classifies the point cloud into ground and non-ground using a deep learning model. The non-ground points are then interpolated and filtered to generate a higher-resolution input for the second level (L2), which further distinguishes between vegetation and structures. The integration of both segmentation levels results in a Digital Feature Model (DFM) that accurately preserves structural information even in densely vegetated environments.

Moreover, the scalability of the method is not tied to the addition of new semantic classes, but rather to the refinement of the classification performance within existing categories. In particular, the system has shown increasing accuracy in recognizing Mediterranean maquis vegetation, as well as in distinguishing subtle archaeological features that do not conform to large-scale, monumental structures. This includes remains from different historical phases, often shallow, eroded, or fragmented. Such adaptability reinforces the robustness of the classification pipeline when applied across heterogeneous Mediterranean environments.

5. Conclusions and Future Directions

The integration of AI techniques with UAV-acquired LiDAR data has opened new frontiers in Mediterranean landscape archaeology. The experiences at Roselle and Castel Porziano demonstrate how a common processing methodology, when properly adapted, can yield significant insights even in challenging environmental conditions. Beyond the immediate results, the broader impact lies in the consolidation of a shared and reproducible workflow that aligns with current efforts in preventive archaeology, heritage conservation, and interdisciplinary research. By sharing methods and critical reflections, this contribution aims to support the wider adoption of LiDAR and AI in archaeological practice. Further steps will include the integration of deep learning models, the development of cloud-based processing platforms, and the extension of the pipeline to additional case studies across the Mediterranean basin.

Furthermore, the methodological transferability is reinforced not by the expansion of semantic classes, but by the improved learning and discrimination within core categories, especially vegetation and archaeological structures. The system's ability to detect varied and often inconspicuous features, including diachronic and low-relief elements, highlights its potential for broader application in archaeological research across different Mediterranean landscapes with complex and diachronic approaches.

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