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Digital Documentation and 3D Modeling of Archaeological Landscapes

Dr. Raja Shaheen Alhammadi

University of Dubai

Abstract:

The digitalization of archaeological landscapes may be considered a significant methodological breakthrough in heritage science. This paper discusses the concept of digital documentation and three-dimensional modeling through photogrammetry, Light Detection and Ranging (LiDAR), Geographic Information Systems (GIS), Structure from Motion (SfM), and Ground Penetrating Radar (GPR) and their impact on theory and practice in the field of archaeology.

The study reviews the history of the process from traditional manual approaches to computer-aided precise documentation techniques, with a focus on the key stages and turning points introduced by satellite-based remote sensing technologies, drone aerial surveying, and the democratization of consumer-grade laser scanning technologies. Critical discussions of the methodologies and workflows are complemented by case study examples from some of the most important archaeological landscapes around the world, from prehistoric megalithic landscapes to submerged coastal settlements, urban landscapes, and desert geoglyph landscapes.

At its core, this work asserts that digital documentation and 3D modeling are not merely additional methodologies but, in fact, an epistemological paradigm shift allowing archaeologists to think beyond site-level documentation and instead engage with a more landscape-level, deep-time, multiscaling interpretive methodology. This has significant repercussions for heritage management, public outreach, and cross-disciplinary collaboration, which require a renewed investment in standardization within the global archaeological community.

Keywords: Archaeological Landscapes, Digital Documentation, 3D Modeling, Photogrammetry, LiDAR, GIS, Remote Sensing**.**

Introduction

Archaeological landscapes are arguably one of the most intricate and vulnerable forms of record of human civilization. While artifacts or architectural monuments may represent specific moments in time, archaeological landscapes embody a vast range of accumulated human intervention, environmental evolution, and cultural development over vast scales of space and time. Documenting, interpreting, and preserving such complex records over long periods of time require a methodology appropriate to such complexity, a requirement which traditional manual approaches have consistently failed to fulfill (Quattrone, 2024).

The advent of digital documentation technologies over the past three decades has revolutionized the potential of archaeologists to document, model, and interpret landscapes with unprecedented accuracy and efficiency. From the replacement of ground-based total stations with laser scanners, to the replacement of aerial photography with drones and multispectral sensors, to the replacement of hand-drawn section drawings with photogrammetric point clouds, however, this revolution is more significant than merely an improvement in technology (Moullou et al., 2023). It is, in fact, a reconceptualization of what archaeological data is and what potential it holds, from static and one-dimensional paper records to dynamic, multidimensional, and re-analyzable digital data (Scott et al., 2021; Unhammer et al., 2024).

In this respect, three-dimensional (3D) modeling, in particular, has established itself as a fundamental component of the digital archaeological toolkit, with its potential to reconstruct landscapes in virtual space providing a crucial link between data and narration, and thereby overcoming the chasm between data and interpretation in a very powerful and evocative manner. When combined with geographic information systems (GIS), chronometric databases, and paleoenvironmental reconstructions, 3D models have the potential to provide a powerful research environment that is capable of sustaining research programs of considerable duration and scope (Kim & Ahn, 2025; Richards-Rissetto, 2017).

This paper provides an overview of the current status of digital documentation and 3D modeling as it is employed in the context of archaeological landscapes. It considers the technological underpinnings of key methodologies, their application to various types and geographical locations, and the methodological, ethical, and institutional issues that accompany their adoption. The article also considers the future directions that will be provided by developments in artificial intelligence, augmented reality, and computational heritage science. At the same time, the argument is advanced that digital landscape archaeology is not merely an improvement upon previous methodologies, but rather a new discipline with unique epistemological commitments and transformative possibilities.

Historical Context and Methodological Evolution

From Sketch to Survey: Pre-Digital Documentation

The documentation of archaeological landscapes has a long and varied methodological history. Antiquarians of the seventeenth and eighteenth centuries used artistic illustration and written description as their principal recording media, and although their written records are often loosely written, they nevertheless retained a record of landscapes and antiquities that have since disappeared or become obscured (Shanks & Witmore, 2010). The professionalization of the discipline in the nineteenth century led to a more rigorous approach, with contour survey maps, plans, and triangulated section drawings becoming standard documentation tools. The adoption of plane table survey and aerial photography in the early twentieth century revolutionized the scope of archaeological documentation, allowing features not visible at ground level to be identified and mapped (Bewley, 2003).

By the mid-twentieth century, fieldwork methodologies had congealed into a series of established conventions: drawn site plans on a specific scale, photography on a specific film type, context sheets in written form, and Harris matrix diagrams of stratigraphic relationships (May, 2020). While these conventions had been analytically quite successful, there were also significant limitations in the density and flexibility of the resulting data set. The physical media of paper is inherently ephemeral and subject to physical degradation; drawn site plans are subject to the bias of the human interpreter; photography requires physical storage and cataloging of media (Heitman, 2017). The translation of knowledge from field to archive and from archive to publication involved a series of lossy transformations that necessarily reduced the informational value of the original observation (Ward, 2022).

The Digital Turn in Archaeological Documentation

The advent of digital technologies in archaeological fieldwork started slowly in the 1980s and increased exponentially in the 1990s and 2000s. The initial applications were in data management, as relational databases replaced traditional paper-based finds registers and simple computer-aided design (CAD) programs enabled the digital drafting of site plans (Chakrabarty, 2007). The advent of Total Station surveying technology allowed for the direct capture of 3D coordinates in the field, replacing traditional plane table methods and greatly reducing the post-survey data entry burden. Global Positioning System (GPS) technology, becoming more readily available in the mid-1990s, extended the precision of spatial data capture to open landscape survey situations, where triangulated station networks were impracticable (Sylaiou et al., 2025).

The late 1990s witnessed the widespread adoption of GIS platforms, such as Environmental Systems Research Institute’s (ESRI) ArcGIS and the open-source alternative Geographic Resources Analysis Support System (GRASS) GIS, which revolutionized the practice of spatial analysis in archaeology (Wieczorek & Delmerico, 2009). GIS technology made it possible to integrate and cross-reference various types of spatial data, ranging from soil geochemistry to transcriptions from aerial photographic data, within a single geospatial framework (Menéndez-Marsh et al., 2023). This led to a conceptual revolution in the way that archaeologists think about the scale at which to analyze sites, from a focus on sites as individual units of analysis to the potential for modeling sites as nodes within larger territorial systems conditioned by factors such as topography, hydrology, and visibility (Menéndez-Marsh et al., 2023; Verhagen, 2018). The early twenty-first century marked the maturation of laser scanning and photogrammetry as documentation technologies deployed in the field. Terrestrial laser scanning (TLS), which can produce up to millions of 3D measurement points per minute, enabled the documentation of entire monument complexes with millimetric precision within a matter of hours rather than days (Rüther et al., 2012). At the same time, developments in photogrammetric software, especially the creation of structure-from-motion (SfM) algorithms, made 3D model creation accessible to everyone, allowing accurate spatial reconstruction based on overlapping photographs taken with standard digital cameras (Eltner & Sofia, 2020). These developments laid the technical and conceptual foundations for contemporary digital landscape archaeology.

Core Technologies in Digital Documentation

Photogrammetry and Structure-from-Motion

Photogrammetry, the process of extracting dimensional information from photographs, has its roots in the mid-nineteenth century. Yet, modern photogrammetry in archaeology is primarily made possible by SfM algorithms that automatically recognize feature points in multiple images and simultaneously compute camera positions and point clouds (Marín-Buzón et al., 2021). This eliminates the requirement for known camera positions and stereoscopy equipment, allowing any researcher with access to a digital camera or smartphone to accurately reconstruct geometrically correct 3D models of archaeological features (Table 1).

From a practical point of view, the SfM process generally entails the systematic capture of hundreds to thousands of images from diverse viewpoints and elevations, followed by image processing in specific software packages like Agisoft Metashape, Reality Capture, or open-source alternatives like Meshroom and OpenDroneMap (Al Khalil, 2020). In the end, dense point clouds, textured polygon meshes, and orthophoto images are generated, often with georeferencing when control points are provided, with resolutions often exceeding one millimeter at close range. Another important feature of SfM photogrammetry is its scalability. Indeed, this technique has been successfully employed to capture images of individual pieces of pottery, sections of trenches, standing structures, and even entire valley landscapes when combined with drone-based image capture.

The use of drone-based photogrammetric surveys, which is now ubiquitous in archaeological surveys, has significantly changed the way landscape surveys are carried out. For instance, fixed-wing and multi-rotor unmanned aerial vehicles (UAVs) with cameras and other multi-spectral and thermal imaging equipment can be employed to photograph large areas of the landscape in one flight, creating orthophotomaps and digital surface models (DSMs) at resolutions ranging from two to five centimeters, allowing for the detection of subtle earthworks, crop marks, and surface scatters that would otherwise be invisible to the naked eye (Colomina & Molina, 2014).

LiDAR and Terrestrial Laser Scanning

Light detection and ranging, or LiDAR, systems work by determining the distance between the device and an object by sending out laser beams and detecting the return time (Li et al., 2024). This system provides accurate 3D data for surveyed surfaces. In the field of archaeology, LiDAR systems have been highly effective when employed as an airborne system. Airborne systems that are capable of sending out multiple pulses for each return from a laser are highly effective in detecting the bare earth beneath a forest canopy, which contains human alterations to the landscape from earlier eras (Hollaus et al., 2007).

The implications of airborne LiDAR for the discipline of landscape archaeology have been nothing short of revolutionary. LiDAR surveys of the Maya lowlands in Belize and Guatemala, from the mid-2000s and expanded dramatically from 2016 with the Patrimonio Cultural y Natural Maya (PACUNAM) LiDAR initiative, have uncovered tens of thousands of previously unknown structures such as field systems, causeways, reservoirs, fortifications, and settlement mounds that have dramatically changed our understanding of the Maya landscape and population density (Canuto et al., 2018). Similarly, LiDAR surveys of the Angkor landscape in Cambodia, the Caracol landscape in Belize, and the Amazonian Basin have consistently shown that pre-colonial civilizations had a much more complex and sophisticated command of the landscape than was previously thought possible with traditional ground survey techniques (Chase et al., 2012; Evans & Fletcher, 2015).

For TLS, this approach has the advantage of using instruments such as the Leica ScanStation or FARO Focus that can acquire a surface at a point density of more than one thousand points per square centimeter, thereby recording textures and other features that might not be visible in photogrammetry under adverse lighting conditions (Newnham et al., 2012). TLS is particularly useful for documenting standing architecture, rock art panels, and sections that rely on the morphology of the surfaces for critical interpretation. Scanning from multiple stations, with each station set to avoid occlusions, has been shown to be capable of documenting complex architectural environments completely in 3D.

Ground-Penetrating Radar and Subsurface Sensing

The documentation of archaeological landscapes must, therefore, go beyond the surface to incorporate subsurface structural complexities. One of the most frequently utilized geophysical survey methods for such documentation is ground-penetrating radar (GPR), which utilizes high-frequency electromagnetic pulses to survey subsurface structures and analyze their reflected signals to generate 2D radargrams and 3D volumetric models of subsurface features (Kwan & Lai, 2024). GPR survey grids, if subjected to time-slice and 3D visualization processing, often provide a very clear picture of the extent, depth, and internal configuration of buried walls, pits, floors, and cavities.

Other frequently utilized geophysical survey methods for archaeological landscape documentation include magnetometry, which measures variations in soil magnetic characteristics resulting from burning, biological activities, or fired clay; electrical resistivity tomography (ERT), which maps subsurface moisture variations resulting from buried features; and seismic survey methods, which are often utilized in the detection of subsurface architectural complexes of very large scales (Milo et al., 2022). The fusion of various geophysical survey data in GIS environments enables the mapping of complex buried landscapes in detail and density that would be economically impractical to investigate using traditional excavation methods.

Remote Sensing and Satellite Imagery

Remote sensing using satellites has made a huge contribution to the documentation of landscapes on a larger scale, especially in areas that are inaccessible due to political instability, environmental unfriendliness, or sheer size of the areas to be explored. Very high resolution commercial satellites such as WorldView-3, Pleiades, and Satellite Pour l'Observation de la Terre (SPOT) provide panchromatic imagery at sub-metric resolutions along with multispectral imagery in visible, near-infrared, and shortwave infrared regions that can be used to identify crop marks, soil marks, and vegetation anomalies that point to buried archaeological features in areas as large as hundreds of square kilometers (Agapiou et al., 2014; Conserva et al., 2025).

Synthetic Aperture Radar (SAR) technology, which allows for the visualization of the ground surface even when obscured by cloud cover and detects minute changes in the ground surface, has been utilized for the documentation of earthwork complexes, irrigation canal systems, and ancient road systems in arid and semi-arid regions characterized by variations in soil moisture that improve the visibility of such features (Das et al., 2025). Thermal infrared remote sensing is useful in regions with extreme temperature differentials and can help identify buried thermal features such as those around stone structures and pit fillings with moisture retention properties (Casana et al., 2017). The free availability of global remote sensing datasets such as National Aeronautics and Space Administration’s (NASA) Shuttle Radar Topography Mission (SRTM) digital elevation data and the Japanese Aerospace Exploration Agency's (JAXA) ALOS World 3D topographic model has opened the door for the global scientific community to perform first-order topographic analysis on landscapes of interest (Uuemaa et al., 2020).

Table 1. Comparison of Major Digital Documentation Technologies in Archaeology

Technology	Principle	Data Output	Advantages	Limitations	Typical Applications
Photogrammetry (SfM)	Image-based 3D reconstruction using overlapping photographs	Point clouds, textured meshes, orthophotos	Low cost, high accessibility, scalable	Dependent on lighting and image quality	Artifact modeling, site recording, UAV surveys
LiDAR (Airborne/TLS)	Laser pulse return measurement	High-density point clouds	High precision, penetrates vegetation	Expensive, large data volume	Landscape mapping, forested site detection
GIS	Spatial data integration and analysis	Layered geospatial datasets	Multi-source integration, analytical capability	Primarily 2D limitations (improving with 3D GIS)	Spatial analysis, predictive modeling
GPR	Electromagnetic subsurface sensing	Radargrams, 3D subsurface models	Non-invasive, detects buried features	Sensitive to soil conditions	Burial detection, subsurface mapping
Remote Sensing (Satellite/UAV)	Multispectral and thermal imaging	Raster imagery, spectral indices	Large-scale coverage, inaccessible areas	Resolution and atmospheric limitations	Landscape survey, anomaly detection

Three-Dimensional Modeling Workflows

Point Cloud Processing and Mesh Generation

The raw output from both the photogrammetric and the laser scanning processes is the point cloud, defined as "a set of discrete coordinate measurements, potentially including color, intensity, and return time, that together describe the geometry of the surface or volume under investigation." Point clouds from large-scale landscape documentation processes can contain billions of individual points, creating significant problems in processing, visualization, and analysis that are best addressed through specialized computing infrastructure and software environments (Dumic & Da Silva Cruz, 2025).

Point cloud processing generally consists of a series of steps including noise filtering, outlier removal, multi-data set registration to a unified coordinate reference system, and finally, classification, which assigns points to a set of semantic categories such as ground surface, vegetation, structure, etc. Classification of airborne LiDAR point clouds, particularly, relies heavily on machine learning approaches to ground/above-ground discrimination to generate bare earth DEMs, which form the primary analytical product in landscape archaeology (Mahir et al., 2025). Once classification has been accomplished, point clouds are usually reduced in density through a process known as decimation or spatial subsampling, which precedes conversion to more commonly used mesh or raster formats.

The process of polygon mesh generation fits the interconnected triangular facets into the point cloud surface and generates a continuous 3D representation that can be visualized and analyzed for physical fabrication. The quality of the generated mesh depends on the trade-off between geometric fidelity and computational manageability. The meshes contain millions of triangles that provide a detailed representation of the object's surface and need powerful hardware for visualization and real-time manipulation in game engines and web applications (Wongwaen et al., 2012). The process of photorealistic visualization involves projecting the photographic texture onto the object's surface and is called texture mapping.

Digital Elevation Modeling and Terrain Analysis

The digital elevation model is arguably the most analytically flexible product of landscape documentation, as it encodes topographic information in a gridded raster format that facilitates the production of many types of derived analytical layers. Slope, aspect, hillshade, curvature, topographic wetness index, and viewshed models are all computationally automatable from a high-resolution DEM, facilitating quantitative characterizations of landscape morphology that inform various types of spatial analysis of site distribution, territorial organization, movement networks, and environmental conditioning of human behavior (Shabbir et al., 2026).

Topographic analyses carried out specifically for archaeological purposes frequently center on the detection and characterization of anthropogenic landforms such as platform mounds, field boundary lynchets, sunken roads, terraced hillslopes, and defensive earthworks that reflect the cumulative history of human alteration. Techniques such as Local Relief Modeling (LRM), Sky View Factor (SVF) analysis, and Multi-Scale Integral Invariant filtering have been designed to improve the detectability of anthropogenic details in DEM data, especially in environments with low natural relief variability compared to the scale of anthropogenic features, as compared to traditional hillshade visualization (Orengo & Petrie, 2018; Zakšek et al., 2011).

Paleoenvironmental Reconstruction and Past Landscape Modeling

The extension of 3D modeling to reconstruct past landscape configurations also offers a solution to the prime problem in archaeology, namely, to understand human behavior in environmental contexts that are no longer present on the Earth’s surface. Sea level changes since the Last Glacial Maximum have resulted in the inundation of millions of square kilometers of potentially habitable continental shelves, which may have stored early evidence of human coastal adaptations and maritime behaviors. Bathymetric survey, together with sedimentological coring and paleoenvironmental modeling, offers a solution to reconstructing the submerged landscapes, which provide a framework for surveying underwater sites (Davis et al., 2024).

Alluvial geoarchaeology uses coring transects, geophysical surveys, and sedimentological studies to investigate river channel migrations, floodplain development, and old landscape surfaces in riverine environments where stratified sites are covered by several meters of overbank sediments (Ferring, 2001). 3D models of old landscape surfaces, populated by chronometric data from dated sedimentary contexts, can be used to spatially and temporally locate site distributions in relation to reconstructed environmental conditions, providing an empirical basis for human-landscape interaction studies.

Immersive Visualization and Virtual Reality

The incorporation of 3D archaeological models with virtual reality (VR) and augmented reality (AR) media offers tremendous potential for both research and communication with a broader audience. Immersive virtual reality environments, available via consumer technology such as Meta Quest or Varjo, enable researchers to interact with archaeological reconstructions on a human scale, evaluating spatial, visual, and kinetic relationships in a manner that is difficult to achieve via visualization on a computer screen alone (Cassidy et al., 2019). Visibility analysis, architectural acoustics, and landscape phenomenology have all been aided by the immersive qualities of VR environments.

Platforms for game engines, such as Unreal and Unity by Epic Games and Unity Technologies, respectively, have also become the primary platforms for the development of interactive archaeological visualizations, as they provide physically accurate rendering, real-time lighting simulation, and scripting facilities that are becoming more and more accessible to non-programmers (Laksono & Aditya, 2019). The distribution of real-time 3D models through web platforms utilizing WebGL and WebXR technologies has also made the dissemination and sharing of interactive 3D site models as part of digital journal articles and online heritage sites more democratized.

Landscape-Scale Analysis and Geographic Information Systems Integration

Spatial Databases and Multi-Layer Integration

GIS plays a role as the integrative analytical core of digital landscape archaeology, offering the georeferenced space in which data from disparate sources, including remote sensing, geophysical survey, excavation, environmental studies, and historical cartography, may be registered, cross-referenced, and analyzed. Current projects in archaeological GIS increasingly make use of the infrastructure of enterprise spatial databases, typically implemented using PostgreSQL servers supporting PostGIS extensions, to facilitate concurrent multi-user access and integration with web mapping services (Magyari-Saska, 2015). The organizational complexity of large landscape databases, including tens of thousands of digitized features and associated attribute, stratigraphic, and chronometric information, requires advanced data modeling and schema design to ensure analytical integrity.

The integration of 3D survey data with GIS environments has traditionally been limited by the inherently 2D nature of the data models employed by most GIS systems. Developments in 3D GIS environments, such as ESRI's ArcGIS Pro 3D Analyst extension and alternative open-source options such as Quantum Geographic Information System (QGIS) in conjunction with the QGIS2threejs plugin, are helping to alleviate these limitations and provide the ability to visualize and analyze true 3D feature geometries within the GIS environment (Khan & Mohiuddin, 2018). Specialized systems such as Rhinoceros 3D in conjunction with the Grasshopper plugin or the archaeological data management system Archaeological Recording Kit (ARK) provide alternative integration pathways with differing emphases in the support of 3D analytical functionality (Vogler et al., 2025).

Predictive Modeling and Site Distribution Analysis

A major use of GIS in landscape archaeology has been concerned with the spatial analysis of site distribution across documented landscapes, which attempts to identify environmental, topographical, and social factors that influenced the siting of human settlements, ceremonial monuments, and activity locations across space. Predictive modeling, which attempts to generate a probability surface representing the probability of encountering site features in unsurveyed regions, relies on correlating site locations with environmental variables derived from DEM, soil, geological, and hydrological data sets, which may employ statistical techniques such as logistic regression, maximum entropy modeling (MaxEnt), and machine learning classifiers (Jo et al., 2025).

One such form of analysis, viewshed analysis, which looks at the viewshed from particular locations in the landscape, has been widely employed in the archaeology of monumental landscapes to investigate the intervisibility between monuments, settlements, and natural features (Supernant, 2014). The cumulative form of viewshed analysis, which looks at multiple viewshed results, may be employed to investigate communal visibility and potentially shed light on the demarcation of territory, choreographing ceremonies, and the construction of social landscape meaning. Least-cost path analysis, which looks at the most efficient path through the landscape, taking slope, vegetation cover, and water bodies into account, may be employed to investigate ancient road networks and connectivity between sites.

Temporal Modeling and Landscape Dynamics

One of the particular challenges associated with landscape archaeology is that there is a need to make sense of the spatial patterns created by the accumulation of human activity across a series of, often overlapping, temporal periods. The same landscape surface might simultaneously retain evidence for Iron Age field systems, Roman villa landscapes, Medieval ridge-and-furrow agriculture, and post-Medieval drainage systems – a palimpsest of anthropogenically modified landscapes that requires complex analysis to disentangle. Digital media have significantly enhanced the potential for modelling temporal landscape dynamics, thereby facilitating the visualization of landscape transformation through the use of time-stamped GIS layers, animated DEMs, and period-specific 3D models.

In addition, Bayesian chronological modeling, which incorporates stratigraphic data with radiocarbon and other chronometric data in a probabilistic framework, is beginning to offer a temporal framework in which spatially distributed data can be integrated and organized. OxCal, a software package developed by Bronk Ramsey of Oxford University, is now de rigueur for Bayesian date modeling in archaeological contexts, and there is current effort to develop data standards to permit Bayesian chronological models to be incorporated in a GIS spatial database, allowing for integrated spatiotemporal data analysis (Bronk Ramsey, 2013).

Case Studies in Digital Archaeological Landscapes

The Maya Lowlands: LiDAR and Forest Canopy Penetration

The PACUNAM LiDAR Initiative, established in 2016 as a partnership between various research organizations, with the National Center for Airborne Laser Mapping as technical partner, carried out a LiDAR survey in more than 2,100 square kilometers of the northern Petén region in Guatemala, one of the biggest airborne LiDAR projects in the history of archaeology (Canuto et al., 2018). The results, published in major journals from 2018 onward, revealed more than sixty thousand individual structures and fundamentally changed our view of the populations, agriculture, and urbanism of the ancient Maya.

The surveys found extensive wetland modification schemes, raised field networks, drainage canals, and reservoir complexes, which were capable of sustaining agricultural populations much larger than previously estimated. Large urban centers were found to be connected by formal causeway networks, some of which stretched over fifty kilometers, suggesting a level of political and economic integration much more developed than suggested by the city-state model (Canuto et al., 2018). Defensive earthwork schemes of unsuspected scale and complexity were found surrounding several major centers, suggesting a widespread phenomenon of inter-polity conflict. This was only possible through a landscape-scale perspective provided by airborne LiDAR, since the density and extent of anthropogenic modification were beyond the threshold of detectability of ground-based or conventional aerial survey.

Stonehenge and the Stonehenge Hidden Landscapes Project

The Stonehenge Hidden Landscapes Project, undertaken between 2010 and 2014, involved a wide range of non-invasive survey methods such as motorized ground penetrating radar survey, magnetometer survey, earth resistance survey, ground penetrating survey using a stream electromagnetic (STREAM EM) system, and high-resolution topographic survey in a fifteen square kilometer area around Stonehenge in Wiltshire, England (Gaffney et al., 2012). The project has created the most detailed underground map ever made of the Stonehenge landscape, showing a remarkable density of previously unknown archaeological features. Some of the discoveries included a buried monument of unparalleled proportions, consisting of a row of ninety or so standing stones, later identified as the Durrington Shafts, which were found to be a circle of massive pits, each measuring over five meters in depth and five meters in diameter, in addition to several burial mounds, ceremonial complexes, pits, and linear features extending over several millennia. By incorporating all the survey data within a specially designed 3D GIS environment, it has become possible to examine the inter-relationship between the newly discovered features and the existing database of known monuments, thereby revolutionizing our understanding of the ceremonial landscape around Stonehenge.

Submerged Landscapes of the North Sea

The continental shelf of the North Sea was, during the height of the last period of glaciation and into the early Holocene, a vast inhabited landscape, termed Doggerland by researchers, which gradually sank beneath the rising seas between ten thousand and six thousand years Before Present (Hijma et al., 2025). The archaeological investigation of this submerged landscape is one of the most technically challenging tasks currently facing heritage science, and one which demands an integrated approach to offshore geophysical survey, together with sedimentological coring and geoarchaeological investigation of incidental faunal and lithic materials.

Projects such as the Europe's Lost Frontiers initiative, based at the University of Bradford, have collated existing decades-long surveys carried out in the offshore environment to create 3D paleolandscapes, covering areas of hundreds of thousands of square kilometers, to reveal past river systems, lake systems, coastal dune ridges, and estuarine complexes that have played host to Mesolithic human settlement (Vincent & Simon, 2022). These landscapes are providing a framework for sampling programs to obtain organic material for radiocarbon dating and eventually build a body of evidence for one of the most important but least accessible prehistoric cultural landscapes in Europe.

The Nazca Plateau: Remote Sensing and Geoglyph Documentation

The Nazca Plateau in southern Peru, well-known for its vast scale of geometric and biomorphic geoglyphs resulting from the removal of surface pebbles to reveal a lighter-colored substrate, has been the recipient of extensive digital documentation work utilizing satellite imagery, drone-based photogrammetry, TLS, and machine learning-based feature extraction (Sakai et al., 2024). The total count of lines, clearings, trapezoids, and anthropomorphic geoglyphs within the region has been found to be in the thousands, well beyond previous estimates based on aerial photographs.

Machine learning methods in geoglyph detection, especially through the application of convolutional neural networks in satellite and drone imagery, have proven to be effective in detecting undocumented geoglyphs at rates many times higher than human detection rates, thereby presenting a potential solution to the problem of systematically surveying an area that measures over four hundred and fifty square kilometers. The 3D modeling of geoglyph form, as well as the spatial analysis of geoglyph distribution and orientation in relation to the surrounding topography and hydrology, has also contributed to the ongoing debate regarding the potential purpose or ceremonial significance of these remarkable geoglyphs.

Challenges and Limitations

Data Volume and Computational Requirements

The most immediate practical issue facing digital landscape archaeology today is the sheer volume of data which modern survey projects can produce. A LiDAR flight over a large landscape area in a single day can produce hundreds of gigabytes of raw point cloud data, whereas a full-scale photogrammetric survey of a major monument complex can produce point clouds of similar densities, along with textured meshes, which require terabytes of storage. Processing such data requires computational power, multi-core processors, and large RAM allocations, along with GPU acceleration for photogrammetric processing and real-time visualization, which remains beyond the reach of many research institutions, particularly in lower-income countries where many significant archaeological landscapes are found.

Cloud computing environments such as Amazon Web Services, Google Cloud Platform, and Microsoft Azure are increasingly offering viable solutions for the limitations in computational resources, offering a processing infrastructure that is accessible on a 'pay per use' basis. Archaeological data management platforms such as Open Context, Archaeology Data Service, and tDAR provide cloud-based environments for digital data archival on a long-term basis; however, resource limitations and institutional barriers still pose limitations for the use of cloud computing in field archaeology.

Data Quality, Resolution, and Representational Fidelity

The analytical potential of the digital landscape data is critically dependent on the quality, resolution, and representational accuracy of the data, which differ considerably with the acquisition methods and environmental conditions. The models derived from the photogrammetric process under uniform overcast lighting show considerably higher geometric accuracy and texture quality compared to those acquired under directional sunlight with high contrast and deep shadows that interfere with the feature point-matching process. The density of LiDAR data depends on the height of the aircraft and the frequency of scanning and vegetation density, affecting the resolution of the ground surface models in areas with high vegetation density. The quality of the geophysical data is affected by the moisture content of the soil and the technique employed by the operators and the calibration of the equipment.

The fundamental concern of representational fidelity—how accurately digital models represent the real-world archaeological reality—must be constantly subject to critical scrutiny. However precise in their geometric detail, digital models are representations, subject to the parameters of their capture, processing, and visualization, which combine to form what Huggett has termed the 'archaeological knowledge graph': a set of assumptions and decisions that are invisible in the final model but are critical to its interpretative potential (Huggett, 2020). There needs to be greater development of conventions around the documentation and communication of model uncertainties, data qualities, and processing decisions to facilitate critical evaluation and responsible re-use of digital records by future generations of researchers.

Long-Term Digital Preservation

The long-term preservation of digital archaeological data faces different challenges from those faced by physical archives. The first of these is the threat of technological obsolescence. The formats and systems by which computer files and programs communicate with each other are constantly evolving, and the risk exists that a file format may become obsolete during the long term of archaeological curation. The rate of technological innovation in the field of digital documentation technologies is such that data formats and storage formats that were valid a decade ago may now be obsolete.

The archaeological heritage community has responded to this challenge in several ways, including the promotion of open and non-proprietary file formats (such as LAS/LAZ for point cloud data, GeoTIFF for image data, and GeoPackage for vector data), the development of domain-specific metadata standards such as the CIDOC CRM and the London Charter for computer-based visualization of cultural heritage, and the establishment of digital repository networks following the Open Archival Information System standards. However, the actual implementation of effective digital preservation strategies in the archaeological heritage community as a whole remains inadequate.

Ethical, Legal, and Cultural Considerations

Ownership, Access, and Digital Colonialism

The creation of high-resolution digital records of archaeological landscapes has significant implications for data ownership, access rights, and benefits of research. In a number of national and international settings, archaeological data that has been gathered under research permission is legally owned by the state in which the research has been undertaken; however, in a number of instances, the actual control of digital data is in the hands of the research institution or the researcher who led the survey project. This disparity in ownership and custodianship can create a situation in which the people who own the cultural heritage that has been documented do not actually have access to the data that has been created—a form of digital dispossession that has a parallel in the colonial past.

Indigenous groups worldwide have been articulating a desire to be involved in a meaningful way in the documentation and interpretation of their ancestral lands, as well as to have sovereignty over digital records of cultural heritage within their traditional territory. While the CARE Principles for Indigenous Data Governance provide a set of guidelines based on Collective Benefit, Authority to Control, Responsibility, and Ethics in data relationships, their implementation takes commitment and may require data management approaches that are not within the traditional academic open-access paradigm.

The Ethics of Virtual Reconstruction

The construction of hypothetical 3D representations of past landscapes and structures is subject to various interpretive decisions, and such decisions are accompanied by important epistemological and communicative obligations. Indeed, visual representations, and even more so when they are produced in photorealistic style, have the potential to significantly naturalize hypothetical interpretations, even when they are uncertain, and to give them a misleading authority. The distinction between data-based observation and inference is not always clear in the final visualization, and there are problems regarding the responsible communication of uncertainty.

The London Charter, which has been published in 2009 and has been largely adopted as a reference document by the digital heritage community, addresses these concerns by setting out a series of principles for the intellectual transparency and documentation of computer-based visualization, requiring that a visualization project document its reasoning and evidence for specific decisions in reconstruction, identify areas of high and low evidential confidence in its reconstruction results, and ensure that digital visualization is accompanied by commentary that contextualizes the visualization within the wider research framework (Bentkowska-Kafel & Denard, 2016). The Seville Principles provide a set of guidelines for the production quality and academic rigor of visualization in archaeology, as well as for community engagement in virtual heritage projects.

Security and the Dual-Use Problem

The potential for security risks associated with high-resolution digital documentation of archaeological landscapes has been a concern that has been addressed relatively slowly in the field. The potential for publicly available high-resolution 3D models and precise location data for archaeological features to aid potential illicit diggers in the location of features has been a concern that has been raised as a potential issue in the field. The global illicit antiquities trade is one of the most significant threats to the archaeological record as a whole.

The balance between open data principles and site security considerations has no easy solution. Context-dependent access control systems that provide detailed site data for authorized researchers while providing more general or lower-resolution data for the general public that is not sufficient to identify features on a site represent a potential solution to this problem. Working in conjunction with national law enforcement agencies and international organizations dedicated to the protection of cultural property, such as UNESCO and INTERPOL's Works of Art division, can provide a solution to these potential dual-use dilemmas.

Future Directions

Artificial Intelligence and Automated Feature Detection

Artificial intelligence, and specifically deep learning techniques for the analysis of images and point clouds, is arguably the most dynamic frontier in digital landscape archaeology. Indeed, the application of convolutional neural networks (CNNs) to various annotated archaeological data sets has shown remarkable performance in the automatic detection of various types of features, including burial mounds, field systems, kiln sites, and geoglyphs, from various sources such as aerial imagery, LiDAR DEMs, and satellite multispectral images. Transfer learning techniques, in particular, have significantly mitigated the annotation burden, which was traditionally seen as one of the major hurdles for the application of deep learning techniques in the field.

The scalability of AI-assisted feature detection is also important to landscape archaeology, in which the human analysis of large survey data sets for rare features can be time-consuming and prone to human analyst fatigue. Detection schemes in which feature location candidates are automatically identified for human evaluation, but not automatically classified, represent a promising middle ground between fully automated and human-dominated feature detection. Current research focuses on improving the generality of existing feature detection models, which to date have been effective only in landscapes similar to those in which the models were originally trained, as well as the integration of multiple data sources and resolutions within feature detection schemes. This is also supported by the advancement of unsupervised machine learning algorithms for anomaly detection in complex environmental data (Owhe & Durodola, 2025).

Digital Twins and Living Heritage Records

The idea of a digital twin, a digital model that mirrors a physical asset, but is kept up to date and reflects changes to the asset, is a notion that is being considered for application to the management of the archaeological landscape. Instead of a static model being generated at a single time, a digital twin of an archaeological landscape could potentially integrate data from ground-based sensor systems, UAV surveys, and even citizen science observations to provide a constantly updated 3D model of the condition of the site, allowing for near-real-time responses to changes like erosion, unauthorized activity, encroaching vegetation, and other changes to site integrity.

The technological capability for the development of digital twin technologies for heritage sites is rapidly advancing, and this is at least partially driven by the development of smart city and infrastructure monitoring systems that have similar key technological needs. The deployment of sensor systems that can monitor and measure changes in soil moisture levels, ground vibration, temperature cycles, and structural deformations can be implemented in heritage sites that are currently under threat and send automatic notifications to heritage managers when the monitored parameters exceed a predetermined threshold level. The integration of such monitoring systems with 3D models of the landscapes and heritage management GIS systems would offer unprecedented levels of awareness for heritage managers tasked with managing heritage landscapes under threat.

Participatory Documentation and Crowdsourcing

The democratization of photogrammetric documentation tools has also introduced new possibilities for the development of participatory landscape documentation programs involving local communities, heritage volunteers, and citizen scientists as active participants in the construction of the archaeological record. Historypin, Zooniverse, and Mapillary are examples of crowdsourced approaches that have shown potential in the collection and generation of large volumes of geotagged photographic data that can be processed to create 3D models of landscape features.

Community archaeology projects that offer training in digital documentation technologies offer participants a set of valuable technical skills, as well as a form of heritage documentation that can be locally controlled—this represents a partial solution to the issue of unequal access to research benefits. There are now mobile application technologies being developed by research consortium groups in Europe and North America, which are specifically aimed at facilitating community-based landscape documentation projects, utilizing a range of guided photogrammetric capture techniques, attribute recording, and upload to a central database.

Interoperability and Open Standards

Ultimately, however, the successful realization of digital landscape archaeology's analytical potential in the long term will be heavily dependent upon the development and use of interoperability standards to facilitate seamless data exchange and integration across institutional, national, and disciplinary divides. Existing practice has seen a proliferation of disparate data formats, platform-specific metadata standards, and variable coordinate reference systems, all of which have hindered data sharing and comparative analysis. In this respect, the development of open standards such as the OGC's CityGML standard for urban and landscape models in three dimensions, the OASIS Archaeological Finds Terminology standard, and the Linked Pasts project's adoption of Linked Open Data principles for archaeological data have been significant steps forward in the quest for interoperability.

The development of global archaeological landscape data infrastructures, i.e., federations of compatible national repositories with a common set of data standards, vocabularies for metadata, and APIs, would revolutionize the analytical possibilities of digital landscape archaeology by facilitating cross-regional comparative studies at scales currently beyond practical scope owing to data fragmentation. Projects like ARIADNE (Archaeological Research Infrastructure for Archaeological Dataset Networking in Europe) and its global extension ARIADNEplus offer a partial blueprint for such an infrastructure, providing a unified discovery and access portal for catalogue data from dozens of national archaeological data repositories.

Conclusion

Digital documentation and 3D modeling have revolutionized landscape archaeology from a discipline primarily limited by manual surveys and 2D mappings to one capable of interpreting complex multi-temporal landscapes. A combination of technologies such as photogrammetry, LiDAR, geophysical surveys, and satellite imaging enables archaeologists to gain a much deeper understanding of past human activities. For example, studies of Maya lowland regions, the North Sea shelf, Stonehenge, and Nazca have demonstrated that such technologies are capable of detecting levels of human activities that were previously undetectable. This has resulted in major revisions of past narratives. Nevertheless, the full utilization of such technologies lies in overcoming major challenges such as creating an ethical agenda, ensuring long-term data preservation, and promoting interdisciplinarity. By achieving a balance between such approaches, landscape archaeology can gain a much deeper insight into the scale of human history.

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