Multi-temporal UAV-based multispectral analysis for vegetation-related risk assessment in archaeological areas

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Abstract

This study investigates the potential of UAV-based multispectral imagery to support vegetation management in archaeological contexts where structures are preserved underground and direct intervention is limited. The analysis focuses on the grassland covering the buried Roman theatre within the Archaeological Park of Castelleone di Suasa (Italy), exploring the relationship between vegetation spectral responses and the Deteriogenic Index (DI), an indicator that indirectly expresses vegetation-related pressure on buried remains. Vegetation indices derived from multispectral data acquired at two distinct moments within the same vegetative season were analysed in relation to plot-based DI values obtained from floristic surveys. Results show that vegetation dynamics, rather than single-date conditions, provide more consistent information, with inter-seasonal indices highlighting vegetation persistence associated with higher deteriogenic pressure. The calibrated relationship was used to derive a spatial proxy of DI, offering a synthetic and non-invasive tool to support spatially informed and adaptive vegetation management strategies in archaeological parks and contributing to the development of integrated information systems for the analysis and sharing of multidisciplinary environmental data.

1. Introduction

Archaeological parks are complex territorial contexts in which stratified heritage coexists with historical, cultural and environmental values, and where conservation goals are closely intertwined with sustainable development and the everyday life of local communities. Managing these areas therefore requires approaches that go beyond the boundaries of the single site and consider archaeological heritage as part of a broader territorial system (Perna, 2023). More in general, the protection and enhancement of archaeological heritage must be integrated into territorial planning policies, as promoted by the Convention for the protection of the European Archaeological Heritage (O'Keefe, 1993), to support sustainable development and community participation. However, increasing hyper-specialization and limited interdisciplinary communication hinder archaeologists' active role in these processes. Effective involvement in urban and territorial co-planning requires shared languages and tools, such as the proper use of GIS as well as the exploitation of digital tools and remote sensing acquisition (Campana, 2014)(Balla et al., 2019).

This complexity is mirrored in the governance structures that characterise archaeological parks, which are often marked by a fragmentation of responsibilities among multiple actors, including heritage authorities, site managers, local administrations and maintenance contractors. While this multi-actor governance reflects the structural complexity of these landscapes, it often leads to decision making processes that are weakly coordinated and focused on short-term operational needs. As a result, management practices tend to be predominantly reactive, with interventions triggered when problems become visible or urgent, rather than being planned within a preventive and long-term framework. This operational approach contrasts with the principles promoted by the international doctrine for heritage. Documents issued by ICOMOS and ICCROM emphasize the importance of preventive conservation, minimal intervention, and adaptive management, recognizing that the long-term preservation of archaeological heritage increasingly depends on regulating environmental pressures rather than relying on episodic restoration actions (ICOMOS, 1990)(ICCROM, 2004).

More recent European policy documents further highlight that climate-driven impacts on cultural heritage are expected to intensify in the coming decades, calling for integrated management approaches capable of responding to both gradual changes and extreme events (Council of Europe, 1992);(European Commission, 2022). This issue has become increasingly relevant under current climate change scenarios, which are characterised by enhanced variability in temperature and soil moisture regimes. These changes are widely recognised as key drivers of physical, chemical and biological processes affecting buried archaeological materials, including accelerated weathering, salt crystallisation, changes in soil chemistry and increased biological activity (Brimblecombe, 2014), (Sabbioni et al., 2010), (Camuffo, 2014). Additionally, national and international regulations require the development and implementation of a management plan that encompasses the environmental and natural system. Good practices in this regard provide an accurate overview of the geological and botanical–vegetation framework, giving specific attention to the assessment of the landscape context across its different degrees of anthropization. Considering this framework, a challenge lies in the development of more comprehensive and integrated information systems capable of effectively supporting these management plans, ensuring that environmental, archaelogical, geological, and vegetational data can be analyzed and shared within multidisciplinary planning framework.

The philosphy of botanical planning in archaeological sites has long been underestimated, particularly with regard to its integration within broader conservation strategies and its potential educational value. Only in relatively recent decades has the botanical component of archaeological landscapes come to be recognised as a form of cultural and natural heritage in its own right, a shift also reflected in the growing attention paid by national conservation bodies and heritage institutions (Caneva, 1999).

Surface vegetation represents one of the main interfaces through which environmental conditions influence buried archaeological structures. Ground vegetation aid in regulating soil water through evapotranspiration, the process by which water is transferred from the soil to the atmosphere in the form of vapour through plants. In the 1990s, at the archaeological park of Mohenjo-daro in Pakistan, the spontaneous growth of plants was proposed as a natural pump to control the water table in areas near the site (Jansen, 1993). In the early 2000s, English Heritage released the results of a research project focused on the use of grass-based coverings to protect wall crests, carried out at Hailes Abbey (Lowerre, 2012) by the University of Oxford in collaboration with Western Kentucky University. The study included laboratory experiments conducted in an environmental chamber to assess the thermal insulating properties of the vegetal layers, their resistance to mechanical penetration, and their ability to retain moisture. The results highlighted the effectiveness of vegetated coverings as a protective solution for exposed masonry remains. Following comparable conservation approaches, in 2004 the Archaeological Superintendency of Rome implemented a vegetated covering using Sedum acre on the tuff strata supporting the remains of the Domus Tiberiana on the western slope of the Palatine Hill. The intervention aimed to preserve moisture within the substrate in order to limit material decay, provide a non-invasive protective layer compatible with the geological structure, reduce surface water runoff, and prevent the spread of invasive plant species. In addition, the solution was considered easier to maintain and more compatible with the historical and visual character of the archaeological site than conventional wall-crown treatments (De Marco et al., 2005).

This role is closely related to the concept of soft capping, a recognised conservation approach based on the use of vegetated layers as low-impact and reversible protection systems (Lim et al., 2016); (O'Grady, 2018). However, the protective function of grasslands cannot be assumed automatically. If not properly managed, species-rich prairies may include plant species characterised by vigorous growth or deep root systems, which can pose risks to buried archaeological remains through mechanical disturbance and changes in soil hydrology (Caneva et al., 2006). For this reason, effective grassland management requires not only maintaining vegetation cover, but also understanding vegetation composition and its associated level of risk. The plant hazard index proposed by Signorini (1996) provides a useful framework to classify plant species according to their potential impact on archaeological and architectural remains, supporting selective and risk-based management strategies. Recent guidance and research further highlight the need to move beyond uniform maintenance practices towards spatially differentiated interventions, in which management intensity is adapted to local conditions and risk levels (Historic England, 2023). Such approaches can reduce unnecessary disturbance while maintaining the functional role of grassland cover and, at the same time, provide ecological co-benefits when appropriately applied (Rada et al., 2024); (Parmentier et al., 2025). A major practical challenge lies in acquiring vegetation information detailed enough to support these management decisions.In species-rich grasslands, traditional floristic surveys are time-consuming and difficult to apply systematically over large areas. By contrast, vegetation indices derived from high-resolution multispectral imagery acquired from unmanned aerial vehicles are widely used in agriculture and phytosanitary monitoring to describe vegetation vigour, stress and phenological dynamics, and have also been applied in archaeology to detect crop marks associated with buried structures (Atzberger, 2013); (Pinter et al., 2003); (Materazzi and Pacifici, 2022). In these applications, multispectral analyses are typically focused on single crops or dominant species.

Within this framework, the Archaeological Park of Castelleone di Suasa was chosen as a case study because it brings together a variety of management situations within a single site. The park extends over about 90 hectares in a river valley where inhabited areas, agricultural land and semi-natural environments coexist. Inside the park, conservation conditions differ substantially, ranging from excavated and unexcavated areas to residential structures, monumental buildings such as the Coiedii domus, the amphitheatre, and the buried remains of the Roman theatre. This variety makes it difficult to apply uniform vegetation management practices and instead requires approaches that can be adapted to the specific archaeological and environmental setting. In the buried theatre area, vegetation is characterised by a very low and weakly differentiated grass cover. As shown in Fig. 1, this area does not exhibit significant elevation variability, making the use of 3D metrics derived from UAV-LiDAR data ineffective in supporting the analysis of multispectral imagery. As a result, UAV-LiDAR data did not provide additional information relevant to vegetation characterisation, and the analysis therefore relies primarily on UAV-based multispectral imagery Vegetation indices derived from these data are used to investigate the relationship between spectral vegetation responses and plot-based Deteriogenic Index (DI) values. The ultimate goal is to translate this relationship into a spatially continuous raster, capable of representing the potential vegetation-related pressure across the study area and supporting spatially informed management decisions.

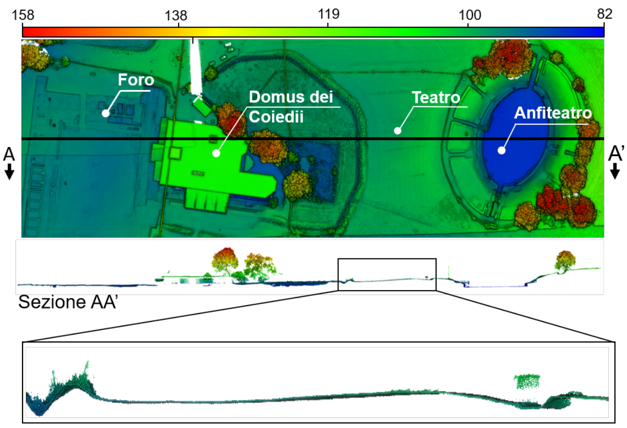


Figure 1. Representation of the LiDAR point cloud and the corresponding longitudinal cross-section, colored according to the Z elevation, with a detailed view of the area of interest.

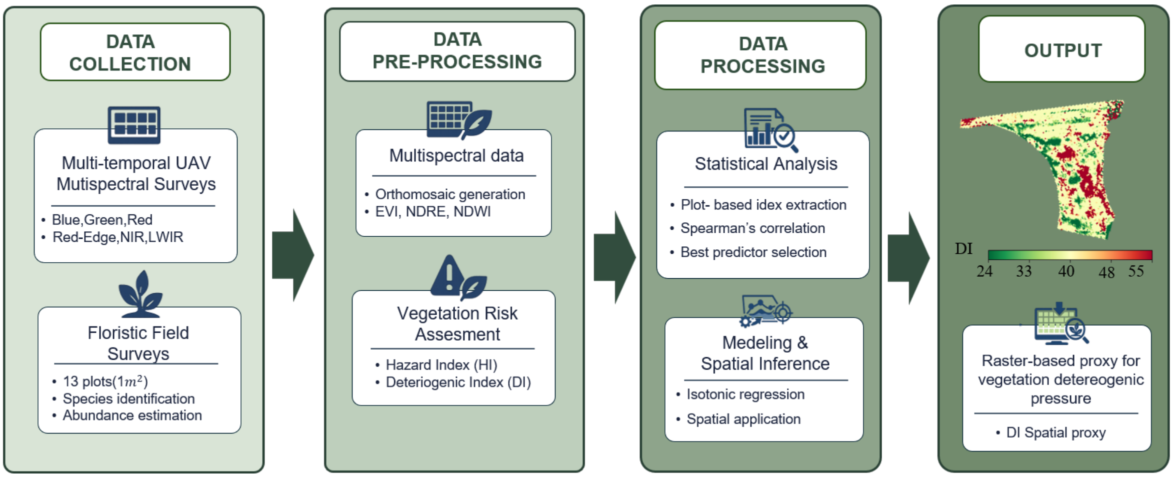
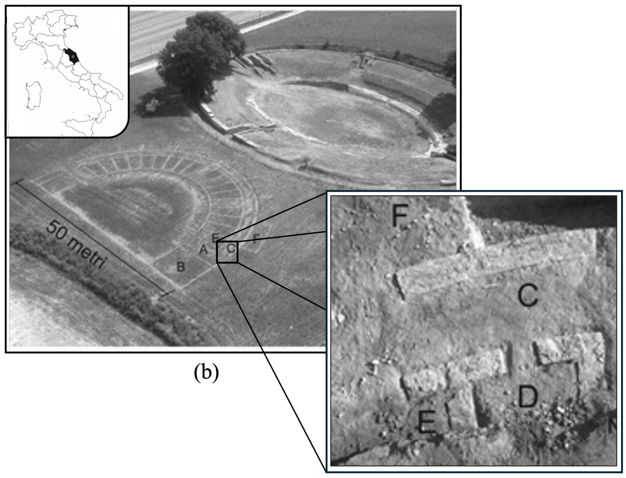


Figure 2. Processing workflow followed in this study, including UAV data acquisition, photogrammetric reconstruction, multispectral analysis, and derivation of a spatial proxy of the Deteriogenic Index (DI).

2. Materials and Methods

2.1 Study area

The study area is located within the Archaeological Park of Castelleone di Suasa, in the middle Cesano River valley, in the Marche region of central Italy. The park preserves the remains of the Roman city of Suasa, which developed from the third century BC along an ancient pre-Roman route on the right bank of the river and reached its maximum expansion during the Imperial period. Today, the archaeological park includes both excavated monumental remains and extensive unexcavated sectors, set within a landscape characterised by the coexistence of agricultural land, inhabited areas and semi-natural environments. Within the ancient urban layout, archaeological remains are distributed along the main road axis, which also structured the surrounding centuriation system. The forum occupied a central position within the city, while residential areas developed on both sides of the main street, including large elite houses that underwent multiple phases of transformation over time. Further south, the urban fabric includes additional residential and public buildings, reflecting the long and stratified occupation of the site. On the eastern edge of the urban area, at the transition towards the surrounding hills, stands the amphitheatre, which represents one of the most prominent monumental structures preserved within the park. The present study focuses on the Roman theatre, located in the southern sector of the archaeological park, in close proximity to the amphitheatre. Unlike other monumental buildings at the site, the theatre is entirely preserved below ground level and is currently covered by grassland, with no architectural elements visible at the surface. Parts of the structure lie immediately beneath the topsoil, making this area particularly sensitive to surface processes and vegetation dynamics. The presence of the theatre was identified in 2003 through aerial photographs acquired during an exceptionally dry summer, when vegetation stress revealed clear crop marks corresponding to the buried structure (Fig.3b)(de Marinis et al., 2012). Subsequent archaeological investigations aimed at assessing the state of preservation focused on the southern sector of the building, including parts of the cavea, the southern aditus and a portion of the scenic building (Fig. 3c). These investigations documented a compromised state of conservation, with no intact floor levels preserved and major collapse of the scenic structures. At present, the theatre is entirely covered by grassland and no architectural remains are visible at the surface. Parts of the structure lie immediately beneath the ploughsoil, explaining the marked visibility of crop marks during dry periods.



(b)

(c)

Figure 3. (b) Theatre vegetation marks and (c) test excavations Fonte: Archivio Soprintendenza Ancona.

2.2 Floristic surveys and vegetation hazard assessment

Species identification represents the foundational step in botanical and ecological studies, as it consists of the accurate recognition and taxonomic attribution of plant species occurring within a given area (Winston, 1999). Correct identification is essential for building reliable floristic datasets and underpins all subsequent analyses. Once species are identified, floristic surveys can be conducted to systematically record the presence, distribution, and abundance of spontaneous and introduced taxa over time, usually across different seasons. These surveys provide the empirical basis for evaluating plant biodiversity, species richness, and conservation value. For botanists and plant ecologists, floristic data are crucial for interpreting vegetation structure, defining plant communities, and carrying out phytosociological analyses. As the survey was carried out in January, it does not document a large proportion of annual species, especially those typically developing in spring. Nevertheless, it allows a reliable assessment of the biennial and perennial components of the grassland, which are particularly relevant in terms of long-term vegetation dynamics.These species are of particular interest in the context of archaeological conservation, as they are generally associated with more developed and persistent root systems and therefore with a potentially higher impact on buried structures. Vascular plant species were identified directly in the field whenever possible. In cases of uncertain identification, plant material was collected and subsequently examined in laboratory. Species identification followed standard floristic references, including Pignatti (1982) and the updated volumes of Flora d'Italia (Pignatti, 1982), as well as Flora Europaea (Tutin et al., 1968–1993). Nomenclature and taxonomic delimitation are consistent with the checklist of the Italian vascular flora and its recent updates (Bartolucci et al., 2018); (Galasso et al., 2018).

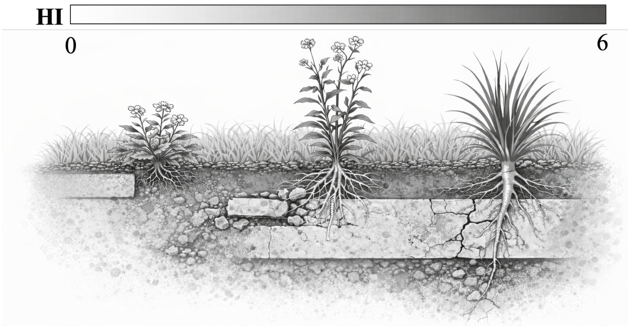


Figure 4. Scheme of vegetation-related hazard based on the Signorini plant hazard index.

To evaluate the potential impact of vegetation on the buried theatre, each recorded taxon was assigned a Hazard Index (HI) following the approach proposed by Signorini (Signorini, 1995),(Signorini, 1996).The Hazard Index was specifically developed for monument conservation contexts and considers plant biological and ecological traits such as life form, vigour, invasiveness and root system characteristics. Values range from 0, indicating negligible hazard, to 10, indicating maximum potential hazard. According to this classification, the highest HI values are associated with woody species, while herbaceous taxa reach lower maximum values, generally not exceeding 6, reflecting their more limited root system development (Fig. 4). From the 13 analysed plots, a total of 21 different vascular plant species were identified. Detailed information on species composition and associated hazard values is reported in Table 1. When applied to a floristic list, however, the HI alone does not account for species abundance and therefore does not allow a quantitative assessment of vegetation pressure at site scale. To address this limitation, vegetation-related hazard was quantified using the Deteriogenic Index (DI), which combines species-specific hazard and abundance.The DI (Eq.1) value ranges from 0 to 60 and is the result of the multiplication between the hazard index of a single species (HIi) and the abundance of a single species (Ai; expressed by the following scale: 1 =¡1%, 2 =1–5%, 3 =6–25%, 4 =26–50%, 5 =51–75%, 6 =76–100%; Braun-Blanquet,1964).the final equations is:

$$DI = \sum_{i=1}^{K} HI_i \, A_i \tag{1}$$

The surveys were carried out within 13 plots of 1 m², selected to capture the spatial variability and compositional diversity of the grassland covering the buried theatre. For each plot, species presence and abundance were recorded, HI values were assigned, and DI values were calculated accordingly. The spatial position of each plot was measured using a GNSS receiver CHCNAV i89 (CHC Navigation, 2023), recording both plot centroids and vertices to ensure accurate spatial correspondence between floristic observations and spatial analyses.

Species	IP
Dactylis glomerata L.	2.1.0
Artemisia vulgaris L.	2.2.0
Bellis perennis L.	2.1.0
Bromus hordeaceus L.	0.0.0
Cerastium glomeratum Thuill.	0.1.0
Cirsium arvense (L.) Scop.	2.2.0
Cynodon dactylon (L.) Pers.	2.2.0
Diplotaxis erucoides (L.) DC.	0.2.1
Dittrichia viscosa (L.) Greuter	3.0.2
Erigeron canadensis L.	0.2.1
Erodium malacoides (L.) L'Hér.	0.1.0
Geranium molle L.	1.0.2
Geranium pusillum L.	0.2.1
Hordeum murinum L.	0.0.0
Picris hieracioides L.	0.2.1
Plantago major L.	0.1.0
Stellaria media (L.) Vill.	0.1.0
Trifolium repens L.	2.1.0
Verbascum blattaria L.	1.2.0
Verbena officinalis L.	2.1.0
Veronica agrestis L.	0.1.0

Table 1. IP Index of the surveyed species.

2.3 UAV-based multispectral data: collection and processing

UAV-based multispectral surveys were conducted at two different times of the year in order to capture temporal variability in vegetation spectral responses. Image acquisition targeted both the visible portion of the electromagnetic spectrum and the Red Edge (RE) and Near Infrared (NIR) bands, which are commonly used as proxies for vegetation vigour, chlorophyll-related activity and water status. Data were collected using a DJI Matrice 350 RTK platform (DJI, Da-Jiang Innovations, Shenzhen, China) equipped with a MicaSense Altum multispectral sensor. The sensor provides five bands in the visible and near-infrared range; plus one thermal channel (LWIR) that was not considered in this study.The first survey campaign, carried out in September, resulted in the acquisition of 844 multispectral images, while the second campaign, conducted in December, produced 953 images.

In standard multispectral photogrammetric surveys using UAS, two main tasks are typically required: the establishment of a Ground Control Point (GCP) network and the execution of photographic acquisition according to a predefined flight plan. Although the UAV platform was equipped with an RTK positioning system, a network of nine Ground Control Points (GCPs) was established to further improve georeferencing accuracy. The GCPs were used to reference the photogrammetric products to the RDN2008 / UTM zone 33N coordinate system (EPSG:6708) and to enhance the overall geometric reliability of the model. The resulting mean positional errors were approximately 3.0 cm in the X direction, 0.8 cm in Y, and 0.3 cm in Z, corresponding to a total horizontal error of about 3.1 cm.

Flights were planned and executed according to recommended photogrammetric standards, using an 80% longitudinal overlap and a 70% transverse overlap to ensure complete coverage of the study area (Mesas-Carrascosa et al., 2017). Data acquisition was carried out at an altitude of approximately 100 m above ground level and a flight speed of about 8 m s^{-1}, resulting in a Ground Sampling Distance (GSD) of 4.40 cm per pixel for the September survey and 4.29 cm per pixel for the December survey. Image processing was carried out using Agisoft Metashape (version 2.2.0; Agisoft LLC, St. Petersburg, Russia) and followed the three main phases of the Structure-from-Motion and Multi-View Stereo (SfM–MVS) pipeline (Fig.5).

First, internal and external orientation of the images was performed. Second, a high-density point cloud was generated. Finally, a three-dimensional mesh and a Digital Elevation Model (DEM) were produced, enabling ortho-rectification and mosaicking of the images.To obtain reflectance values suitable for quantitative analysis, the multispectral images were radiometrically calibrated using solar sensor data through the dedicated Metashape calibration tool. Unlike standard RGB photogrammetric workflows, the generation of a multispectral orthomosaic required exporting a multiband dataset. The orthomosaic bands, initially stored as 16-bit integer values, were normalised by scaling reflectance values to the range between 0 and 1, where full reflectance corresponds to the maximum digital value of 65,535.The final orthomosaics were exported as multiband TIFF files including the Blue, Green, Red, Red Edge, Near Infrared and thermal bands.

Figure 5. Processing workflow illustrating the generation of the RGB point cloud, solid mesh, and elevation model for the area of interest (AOI).

2.4 Multispectral data analysis

The two multispectral orthophotos were analysed using the same workflow, based on the computation of spectral index maps, in order to ensure comparability between survey periods. All post-processing steps were carried out in a Python environment,inside the environment VSC. The orthomosaics were first clipped using the boundaries of the floristic plots. For each plot, three vegetation indices were calculated: the Enhanced Vegetation Index (EVI); (Huete et al., 2002)(Eq.2), the Normalized Difference Red Edge index (NDRE)(Eq.3); (Barnes et al., 2000) and the Normalized Difference Water Index (NDWI); (Gao, 1996)(Eq.4).

$$EVI = 2.5 \cdot \frac{NIR - Red}{NIR + 6 \cdot Red - 7.5 \cdot Blue + 1} \quad (2)$$

$$NDRE = \frac{NIR - RedEdge}{NIR + RedEdge} \quad (3)$$

$$NDWI = \frac{GREEN - NIR}{GREEN + NIR} \quad (4)$$

Together, these indices capture complementary aspects of vegetation condition, including chlorophyll-related activity and water status. From the three indices (Fig.5), a total of fifteen predictive variables were derived. For each index, median values and standard deviations were calculated separately for the September and December datasets to describe both central tendency and within-plot spectral variability. Temporal changes between the two survey periods were further quantified using delta metrics, computed as the difference in index values between September and December. The final delta value was obtained by computing the median of the pixel-wise differences, providing a summary of temporal variation while reducing the influence of outliers.

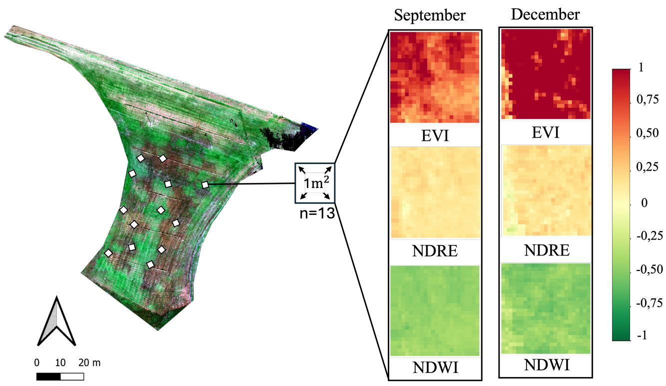


Figure 6. RGB orthomosaic of the study area with the location of the 13 floristic plots (left) and vegetation index maps (EVI, NDRE and NDWI) computed for Plot 12 (right).

To investigate the relationship between vegetation-based predictors and the target variable (DI), we computed Spearman's rank correlation coefficient (ρ) for each spectral index. This non-parametric measure was chosen because it does not rely on distributional assumptions and is well suited to capture monotonic, potentially non-linear relationships, which are common in remotely sensed vegetation data. Unlike Pearson's correlation, which is restricted to linear relationships and can be sensitive to outliers and non-normal data, Spearman's method is based on ranked values. This makes it more robust to irregular distributions and heterogeneous variability, while still preserving information about the direction and strength of the association. In practical terms, Spearman's (ρ) indicates whether DI tends to increase or decrease consistently as a given vegetation index changes, even when the relationship is not strictly linear. For each predictor, statistical significance was assessed using the associated p-value of Spearman's test. The p-value expresses the probability of observing a correlation as strong as the measured one in the absence of any real monotonic relationship. Standard significance thresholds ($p < 0.05$, $p < 0.01$, and $p < 0.001$) were adopted to highlight potentially meaningful associations. However, because Spearman's correlation is non-parametric and does not assume any specific functional form, statistically significant p-values only indicate the presence of a consistent trend and do not describe how this relationship is structured. In this context, p-values should therefore be interpreted as a measure of reliability rather than as evidence of a predictive model. Their meaning must be supported by expert interpretation and by direct inspection of the data, in order to assess the ecological and archaeological relevance of the observed patterns. The correlation analysis was used as an exploratory screening step to identify vegetation indices showing a clear and statistically supported monotonic relationship with DI. This choice is directly linked to the subsequent modeling approach: since the final model is based on isotonic regression, which explicitly enforces a monotonic relationship without assuming a predefined functional form, selecting a predictor that already exhibits a strong monotonic association with the target variable is methodologically consistent. Accordingly, the vegetation index showing the strongest statistically significant monotonic relationship with DI was selected to calibrate the isotonic regression model, with the sign of the correlation determining whether the fitted relationship was constrained to be increasing or decreasing.

3. Results and discussion

The relationship between vegetation spectral properties and vegetation-related deteriogenic pressure was explored by combining UAV-derived multispectral indices with plot-based Deteriogenic Index (DI) values calculated from floristic surveys carried out on 13 plots. This integrated dataset made it possible to examine how different ways of describing vegetation condition relate to potential impacts on buried archaeological structures. When single-date vegetation indices are considered, the results show different and partly contrasting behaviours between the two acquisition periods. In September, EVI and NDRE tend to be negatively correlated with DI, whereas NDWI shows a positive relationship. This suggests that, under late summer conditions, higher vegetation vigour and chlorophyll-related activity are generally associated with lower deteriogenic pressure, while higher vegetation water content may correspond to increased pressure. However, this configuration indicates that, during this period, the interpretation of the relationship between spectral indices and DI is particularly complex and potentially misleading, as vegetation responses are strongly affected by water stress and senescence processes that are not directly related to vegetation-related hazard. However, in December, the pattern changes: EVI and NDRE mostly show positive correlations with DI, and NDWI displays weaker or less consistent relationships. These differences indicate that single-date spectral responses are strongly influenced by seasonal conditions and phenological stage, and that the same index may reflect different ecological processes depending on the time of acquisition. Together, these results suggest that instantaneous vegetation conditions provide only a partial and sometimes ambiguous picture of vegetation-related pressure. Although statistically significant correlations can be identified, their variability across seasons limits their usefulness for a consistent interpretation of deteriogenic processes.

A more coherent picture emerges when multiseasonal metrics, computed as inter-seasonal differences between September and December, are taken into account. Within the same plot-based framework used for floristic characterization and DI calculation, delta indices consistently show stronger and more stable correlations with DI than single-date observations. This suggests that seasonal variations in vegetation condition are more informative for understanding deteriogenic pressure than spectral values observed at a single time. Among the analysed predictors, ΔEVI shows the strongest and most consistent relationship with DI (Fig. 7). In particular, lower ΔEVI values are associated with higher DI scores, while higher ΔEVI values correspond to lower deteriogenic pressure. This pattern suggests that plots characterised by limited seasonal variation in vegetation vigour tend to exert greater potential pressure on buried structures, whereas plots showing a marked seasonal decline in vigour are generally associated with lower DI values. This interpretation is consistent with the floristic observations, where perennial-dominated communities tend to maintain more stable physiological activity over time compared to assemblages dominated by annual species. At the spatial scale, the DI proxy raster derived from the selected vegetation-based predictor reflects the partial and non-uniform nature of this relationship. The resulting distribution is fragmented, with localized areas of higher estimated deteriogenic pressure embedded within zones characterised by moderate or low values, rather than forming continuous gradients across the study area (Fig. 6). This spatial heterogeneity indicates that vegetation-related pressure is unevenly expressed and suggests that, while vegetation dynamics play an important role, additional local factors not directly captured by spectral vegetation indices also contribute to the observed spatial variability.

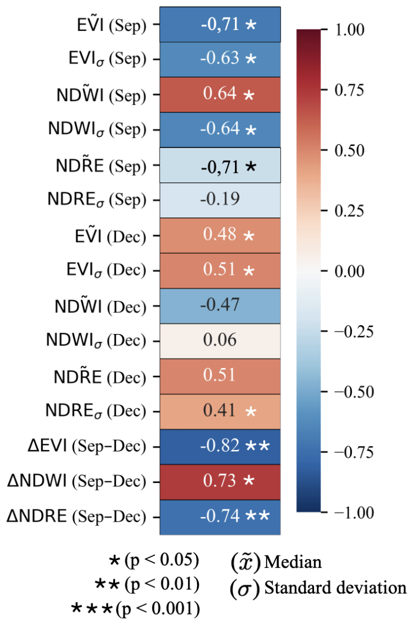


Figure 7. Spearman's rank correlation coefficients.

4. Conclusions

This study addressed the challenge of supporting vegetation management in archaeological parks through tools capable of integrating ecological information with spatially explicit data, in line with the need for preventive and adaptive conservation strategies highlighted in current heritage policies. In complex contexts such as archaeological parks, where buried remains coexist with semi-natural vegetation and heterogeneous land-use conditions, traditional reactive management approaches are often insufficient to mitigate long-term deteriogenic processes. In this framework, the lack of operational tools able to translate vegetation-related risk into spatially continuous and actionable information represents a critical gap.

By combining floristic surveys, plot-based deteriogenic indices and UAV-derived multispectral vegetation indices, this work suggests that vegetation dynamics can be partially quantified and spatially interpreted in relation to potential deteriogenic pressure. The results indicate that single-date spectral observations are strongly influenced by seasonal conditions and therefore provide limited support for consistent risk assessment. In contrast, multiseasonal metrics, and in particular inter-seasonal differences in vegetation indices, capture aspects of vegetation persistence that are more closely linked to the ecological traits relevant for archaeological conservation.

The identification of a strong and consistent relationship between ΔEVI and the Deteriogenic Index highlights the relevance of vegetation stability over time, rather than peak vigour, as a key factor influencing potential impacts on buried structures. This finding directly addresses one of the central issues raised in the introduction, namely the difficulty of assessing vegetation-related risk in species-rich grasslands where traditional floristic surveys are time-consuming and difficult to apply systematically. While field-based surveys remain essential for understanding vegetation composition and ecological traits, their integration with multispectral data provides a scalable means to extend this information spatially and to support spatially differentiated management strategies.

The spatial representation of vegetation-related pressure, illustrated by the DI proxy raster map (Fig. 8), represents a concrete example of how these results can be translated into a basic GIS support tool for archaeological park management. Although the resulting pattern is necessarily simplified and does not capture all site-specific drivers of deterioration, it highlights areas of potential concern and allows vegetation-related risk to be visualised and queried within a spatial planning framework. In this sense, the DI proxy map is not intended as a predictive product, but as an operational layer that can support informed decision-making, prioritisation of interventions and dialogue between archaeologists, ecologists and site managers.

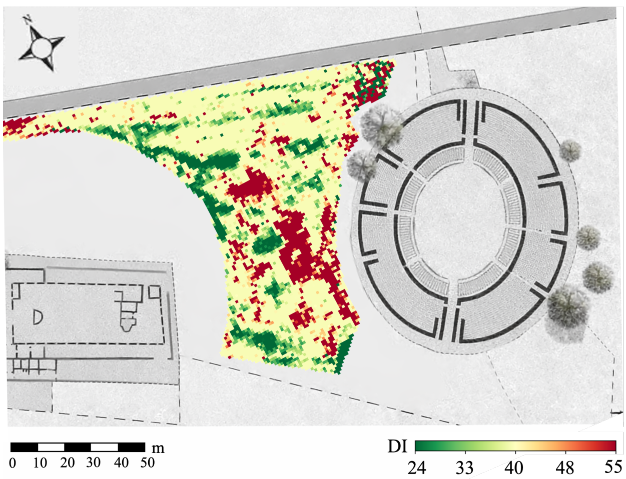


Figure 8. Rappresentation of DI Proxy Raster

At the same time, several limitations of the proposed approach should be acknowledged. First, the ground sampling distance of the multispectral data, constrained by the flight altitude, may limit the detection of fine-scale vegetation patterns, particularly in species-rich grasslands characterised by subtle spatial variability; lower-altitude acquisitions could therefore improve the sensitivity of the analysis. Second, floristic surveys were conducted during the winter season and consequently underrepresent annual species that develop in spring, potentially biasing the assessment towards perennial components that are more visible at the time of sampling. Third, the Deteriogenic Index itself has intrinsic conceptual limitations, as similar DI values may result either from the presence of many low-hazard species or from a smaller number of highly hazardous taxa within a plot. This aggregation may partially obscure differences in vegetation composition and highlights the importance of interpreting DI values in conjunction with qualitative floristic information.

Overall, this work contributes to bridging the gap between detailed ecological knowledge and spatial planning needs in archaeological parks. By showing how UAV-based multispectral imagery can be meaningfully linked to vegetation-related hazard assessments and translated into GIS-ready products, it provides a practical step towards more informed, preventive and adaptive vegetation management strategies, supporting the long-term conservation of buried archaeological heritage within complex and evolving landscapes.

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