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Change Detection analysis of Cultural and Landscape Heritage based on Multispectral and Hyperspectral remote sensing data and algorithm: the case of Appia Antica Park

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Abstract – **In remote sensing multispectral and hyperspectral imaging are a valid method to analyse Earth Observation (EO) data. If multispectral imaging is largely used and well knowed in EO and refers to the scomposition of the spectral range of the instruments onboard in few channels (typically from 6 to 12), hyperspectral Imaging gains a greater spectral resolution and refers to obtain the spectrum for each pixel in the image, with the purpose of finding objects, identifying materials, or detecting processes through the structural analysis of the source (in SWIR range) or chemical behaviour (in VIS range). In this work a multispectral (NDVI) and hyperspectral (red edge slope) technique is used to perform a *Change Detection* (CD) on the vegetation of the Appia Antica Regional Park in Rome. The results show the benefits of these analyses in evaluating the state of landscape and in developing appropriate management projects.**

Keywords: Multispectral Imaging; Hyperspectral Imaging; Change Detection; Appia Antica Park; Landscape Heritage

I. INTRODUCTION

In recent years, mapping urban vegetation distribution has garnered significant interest due to its connection to various research fields, such as urban climate, well-being, and Sustainable Development Goals [1]. While field investigations have limitations in evaluating the dynamic growth status of different plants, remote sensing remote and GIS technology has long been established as an accurate technique for continuous soil monitoring, because of its effectiveness in detecting even the smallest environmental changes. Furthermore, the growing contribution of remote sensing to monitoring and preserving Heritage, both environmental (parks, landscapes, etc.) and cultural (monuments, archaeological sites, etc.) [2] has been fostered by the variety of satellite sensors, free and open access to satellite images, and the use of combined techniques for a more accurate and extensive analysis of CH sites and their surroundings [3]. Indeed, multitemporal analysis conducted on optical satellite images proves to be very useful in the study of changes in the surface characteristics of the soil, in terms of texture, humidity and vegetation cover and has long established itself as an essential practice for monitoring the state of health of the vegetation, supplying indispensable indications for a correct management and planning of the territory [4]. For example, an increase in vegetation cover, beyond the phenological crop cycle, may be a sign of intense agricultural exploitation [5]. At the same time, vegetation indices are input parameters for the study of other risks such as soil erosion and fires. Finally, multi-temporal analyses based on the use of spectral signatures that characterise the type of plant and the calculation of vegetation indices that quantify its moisture content allow the identification and characterisation of weed vegetation, which is the most widespread cause of damage and degradation of the monumental heritage [6;7]. Hence, the definition of a monitoring methodology for plant organisms is a priority in contexts in which the landscape, defined by an anthropic matrix, is dotted with archaeological ruins and vegetation. Is there a method or technology that can increase the resilience of our cultural heritage - both monumental and landscape - now exposed not only to known natural and anthropogenic risks but also to the effects of climate change? It seems essential to identify a procedure that also allows establishing a gradation of priorities on the interventions to be carried out, guaranteeing an early warning system through mitigation strategies [8].

Vegetation is composed by leaves that are characterized by carotenoids and pigments. These are responsible for the

absorption and reflection in various range of energies. Limited to this work we are interested in the pigments that reflects in red and near infrared range. Two different ways to monitoring these absorption (that reflects the health of vegetation [9]) are used and compared each other to distinguish vegetation presence and status in the image. These methods are: 1) the normalized difference vegetation index (NDVI [10]) for the multispectral data (from the multispectral satellite Sentinel 2 [11]) and a Red Edge Score map that assign at each pixel of the image a number that measures the slope of its spectral signature in the red edge range (from the hyperspectral satellite “PRecursore IperSpettrale della Missione Applicativa”, PRISMA [12]).
According to the state of the art [4, 13], mapping and monitoring of urban vegetation in the study area has been mostly conducted with optical and multispectral images which involve the study of the light reflected by the leaves to monitor the state of vegetation. Within this framework, this contribution aims to broaden the monitoring methodology for plant organisms using satellite hyperspectral data (PRISMA) instead of satellite multispectral (Sentinel 2 and Landsat 8 [14]). Indeed, even if these data have a lower spatial resolution (due to the greater spectral sampling) compared to multispectral satellites, they are able to trace more precisely the activity of the chromophores and photoprotectors of the vegetation, which are responsible for their characteristic reflectivity in the spectral zone of the red edge, allowing better quantitative and not only qualitative monitoring of vegetation health, becoming a very effective tool in identifying and characterising weed vegetation, which is the most widespread cause of damage and degradation of monumental heritage [6;7].

II.STUDY AREA

The study area is a cultural and urban context of great importance, the result of complex interactions between man and the natural environment (*Ager Romanus*), through which local communities self-represent themselves *Fig. 1*. The Antique Appian Way Regional Park was established in 1988 in the southeastern part of the urban area of Rome Municipality, around the first consular road, the via Appia Antica. More recently, in 2016, the Ministry of Cultural Heritage identified the Appia Antica Archaeological Park to protect the archaeological remains around the ancient road as a whole, and not only as individual monuments. This vast area of more than 4800 hectares is crucial for the city of Rome in terms of its identity, history, imaginary and environmental quality. It is an area that has been extensively studied for its heritage, being one of the favourite destinations of the XVII and XVIII century *Grand Tour*, but also for its indubitable environmental and ecological qualities that have been preserved since the time of Pope Paul III Farnese [13].

In this vast green area, 85% private and very important in the city ecosystem (43% of flora of Rome and 20% of regional flora), archaeology represents only one of the components of the context, which is actually heterogeneous. Residential, agricultural (primarily wheat fields, that covers more than 50% of the total area) and productive areas coexist together with protected natural and cultural heritage, such as historical elements (i.e., farmhouses) and archaeological remains (i.e., Aqueducts, funerary monuments, catacombs, roman villas and churches) [15].

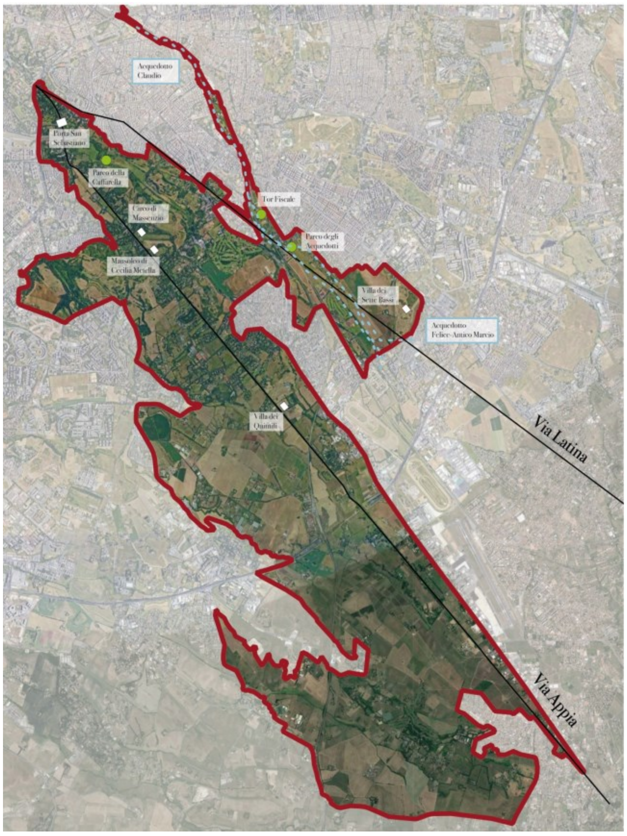

Fig. 1 Map of Appia Antica Regional Park with main localities, archaeological sites and roman streets

Indeed, in the last 200 years the city of Rome has grown intensely around the Appian Way, surrounding the margins of the park: the area south of Rome is one of the most populated areas of the hinterland. As a whole, this cultural heritage landscape reveals a high fragmentation that occurred during the past, whose protection is regulated by Legislative Decree 22 January 2004, n. 42 "Code of cultural and landscape heritage", reformulating in particular the Law 1089 of June 1, 1939 on the "Protection of things of historical and artistic interest".

III. METHODOLOGY

A. Source Data

The following tables shows data acquisition of master and slave images of Sentinel 2 with their NDVI score of pixel 9 and the data acquisition of master and slave images of PRISMA satellite with the Red Edge Score of the pixel in *Fig. 3* in each acquisition. In this section there are also the rasters of master and slave of Sentinel 2 and PRISMA described in the tables and rearranged in RGB channels (channel 3,2 and 1 for Sentinel 2 and channel 33, 23 and 12 for PRISMA satellite).

Table 1. Sentinel 2 Data and NDVI

Sentinel 1	Acquisition Time (yyyy-mm-dd)	NDVI
Master	2019-08-19	0.5
Slave	2022-07-19	0.3

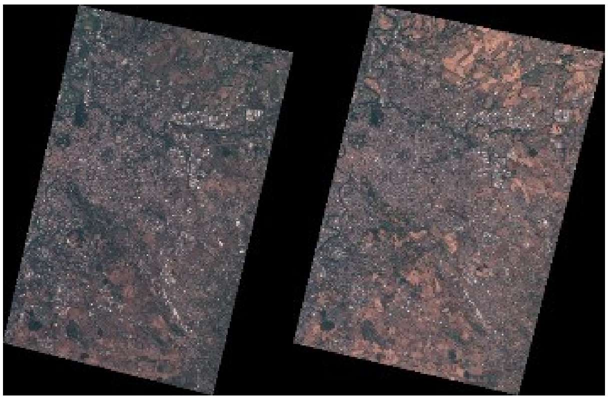

Fig. 2 Rasters of Sentinel 2 in which NDVI is calculated: master is on the left and slave is on the right

Table 2. Prisma Data and Red Edge Score

PRISMA	Acquisition Time (yyyy-mm-dd)	Red Edge Score
Master	2019-12-29	4479
Slave	2022-07-02	835

Fig. 3 Rasters of PRISMA in which Red Edge Score is calculated: master is on the left and slave is on the right

B. Analysis Method

The input data were used for the creation of indices such as the NDVI and the Red Edge Score, as already reported in the literature [10]. The produced maps, described in the following chapters, were analysed using PhotoMonitoring approaches.

PhotoMonitoring is a monitoring approach that utilises the concept of "digital image processing", which involves manipulating digital images to extract valuable data and information. The analysis is performed on datasets of images captured from the same platform, covering the same area of interest but at different time intervals. Specific algorithms are employed to assess any variations in radiometric characteristics (Change Detection) or the spatial displacement that occurred during the time span covered by the image acquisition (Digital Image Correlation). Essentially, digital image processing techniques involve extracting information about changes by comparing different types of images (e.g., satellite, aerial, or terrestrial images) collected at various points in time over the same area and scene [16].

This work involved the use of IRIS software, an innovative software designed for PhotoMonitoring applications developed by NHAZCA S.r.l., a start-up company of Sapienza University of Rome. The change detection method employed in this Software utilises the Structural Similarity Index Measure (SSIM), which was initially developed to evaluate the visual quality of digital television and film images. Rather than directly comparing images, the algorithm measures image quality by comparing them to a reference image. This approach has been widely used for image quality assessment since its development by Wang and Sheikh [17]. This algorithm considers image changes as a combination of three factors: luminance, contrast and texture features. This method operates locally by iteratively assessing the similarity of image segments using a sliding window approach. As a result, it enables the automatic identification of regions within the scene where changes have taken place.

IV. MULTISPECTRAL ANALYSIS

Multispectral imaging refers to the capability of detecting an image in 8 or more spectral bands that are centered in different wavelengths. The main advantage of this, respect the hyperspectral imaging, consists in a major geometrical resolution of the image (broader spectral bands means less photons to keep high signal to noise ratio).

Fig. 4a and *4b* shows the Normalized Difference Vegetation Index of master and slave of *Fig. 2*. These maps are used as input in the Change Detection performed by IRIS software.

In *Fig. 5* is showed the output of the change detection between the *Fig. 4a* and *4b* that shows the changed zones as dark violet pixels and the unchanged as green pixels.

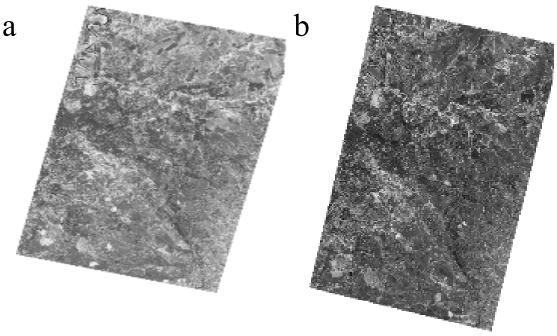

Fig. 4 a) NDVI score map of the master image of Sentinel 2. b) NDVI score map of the slave image of Sentinel 2.

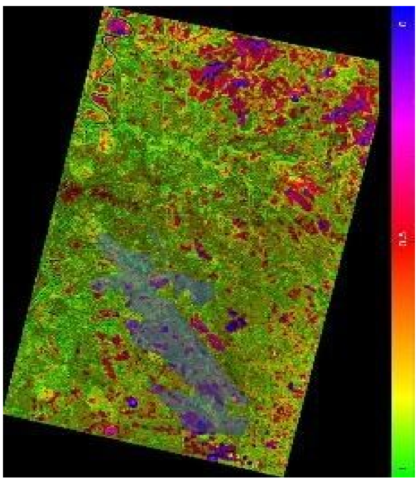

Fig. 5 Change detection performed by IRIS on the NDVI map score of 2019 and 2022.

V. HYPERSPECTRAL ANALYSIS

Differently from multispectral imaging, hyperspectral imaging is composed by a large number of channel (in this case the channels are 232). In this way it is possible to extract the spectral signature of the source analysing the reflection in each band, the ensemble of this reflections is called hyperspectral signature. The range of hyperspectral satellite used for this work is from the blue to the short wavelength infrared; concerning the topic of this work, we are interested in the range from 675 to 754 nm that is called red edge (it is the region between red and near infrared spectral range). Vegetation reflects radiation in this spectral range differently from rocks and non vegetation areas that show a less severe slope in the red edge spectral range.

Fig. 6a and *6b* shows the Red Edge Score maps of master and slave of *fig. 3*. These maps are used as input in the Change Detection performed by IRIS software. In *fig. 7* is showed the output of the Change Detection between the *fig. 6a* and *6b* that shows the changed zones as dark violet pixels and the unchanged as green pixels

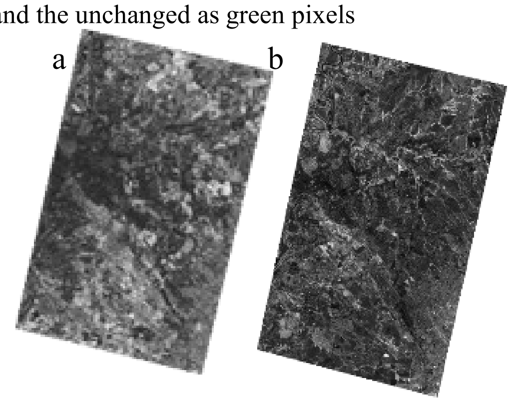

Fig. 6 a) Red Edge Score map of the master image of PRISMA. b) Red Edge Score map of the slave image of PRISMA.

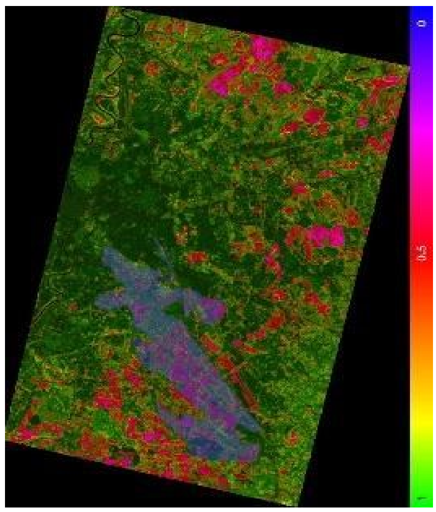

Fig. 7 Change detection performed by IRIS on the Red Edge Score map of 2019 and 2022.

VI.DISCUSSION AND CONCLUSION

The red edge slope algorithm is able to provide a further detail of the state of health of the vegetation by studying the pigments of the leaves. Furthermore, as seen in section V, it is able to detect changes that are not visible in the NDVI classification. This is due to the fact that the NDVI algorithm is not able to trace these changes with only two bands centered in the spectral range of interest (even if they have a higher geometric resolution therefore they generate more resolutive images).

Using each band of this range, it is possible to evaluate the status of vegetation in a more detailed way than NDVI. This is due from the fact that with only two points it is difficult to measure the red edge slope considering only the initial and the final values that characterize vegetation in a pixel. Instead using a greater number of channels in this spectral range it is possible to accomplish mathematical tools and calculations that evaluate the slope of the spectral feature in a broader scale.

As validation we used the database of Google Earth. In *Fig. 9* it is possible to view how vegetation cover is strongly reduced in the slave image. The white frame is a pixel of PRISMA satellite in which the CD of the red edge slope indicates an important change.

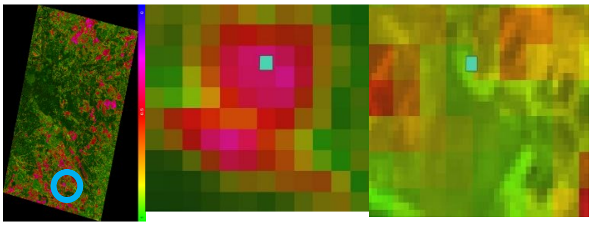

Fig. 8 - A comparison between a zone of NDVI and Red Edge Score map, cyan pixel identifies a pixel of PRISMA in which is calculated validation in fig. 9 and the spectral signature in fig.10. (Left panel) the red edge score map of fig. 7, the cyan circle indicates the zone in which is performed the zoom in of middle and right panel of this figure. (Middle panel) a zoom in of the Red Edge Score map inside the cyan circle. (Right panel) a zoom of the NDVI score map inside the cyan circle.

Fig. 9 - Google Earth images of 2019 (left) and 2022 (right) used as validation of this work. The framed area is the PRISMA pixel (white square) represented as the cyan pixel of fig. 8, in which the spectral signatures were calculated. In fig. 10 As can be seen from the areas circled in red, in 2022 there are much fewer areas of vegetation than in 2019.

As we can see from the tables 1-2 both NDVI and Red Edge Score note that vegetation cover decreases from master to slave, but from the fact that the only possible values of NDVI are included in the range from -1 to 1 the algorithm is unable to detect little change of vegetation respect the more accurate algorithm of Red Edge Score that is not limited by this numerical range. In *Fig.9* in fact the value of NDVI of master is 0.5 and decrease to 0.3 while the value of Red Edge Score of master Image is 4479 and in the slave decreases to 835: this is the main reason that let the change detection on the Red Edge Score to emphasise the zone instead not evident in the change detection of the NDVI maps.

In *Fig.10* spectral signature of the pixel is very different between Master and Slave (and consequently the slope of the Slave pixel is closer to the typical behaviour of soil in the red edge, as the cover vegetation is reduced).

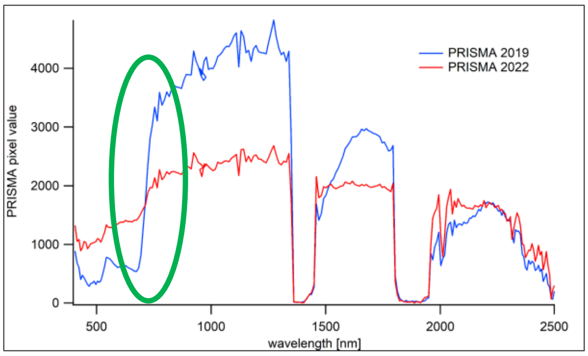

Fig. 10 Spectral signatures of the pixel present in Fig. 9: the signature of 2019 is dominated by vegetation due to the steepness of the red edge section while instead that of 2022 is closer to the behaviour of soils without vegetation (low steepness of the section red edge).

In conclusion, the use of the Red Edge Score through hyperspectral data offers significant advantages compared to the use of NDVI. The primary benefit lies in the increased amount of vegetation information, as the Red Edge Score covers a much broader range of values compared to the limited range of NDVI (-1 to 1). This means that the Red Edge Score can provide information on vegetation within a range extending from positive values, even in the absence of vegetation, to infinity. This capability stems from its effectiveness in detecting vegetation reflectance within this spectral band.

However, there is a notable drawback in utilizing the Red

Edge Score: it results in images with lower geometric resolution compared to multispectral satellite data. This limitation can be problematic if the primary objective is not only to analyse vegetation status but also to precisely assess the geometric extent of vegetation cover within a specific area and monitor changes over time.

Despite these disparities, it is feasible to merge data from both methods to obtain detailed images from both geometric (vegetation extent) and spectral (vegetation status) perspectives. This integration can represent a significant outcome of the study, facilitating a deeper understanding of vegetation conditions. Furthermore, it may be possible to establish parameters and thresholds based on the Red Edge slope that enable the classification of vegetation as healthy or unhealthy, thus contributing to effective monitoring of cultural heritage landscapes. If refined further, this approach could become a valuable tool for quantitative monitoring of vegetation health, proving highly effective in identifying and characterizing invasive vegetation, a prevalent cause of damage and degradation to cultural heritage.

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