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RESEARCH ARTICLE

REVISED A Google Earth Engine-enabled Python approach for the identification of anthropogenic palaeo-landscape features

[version 2; peer review: 2 approved, 1 approved with reservations]

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Abstract

The necessity of sustainable development for landscapes has emerged as an important theme in recent decades. Current methods take a holistic approach to landscape heritage and promote an interdisciplinary dialogue to facilitate complementary landscape management strategies. With the socio-economic values of the “natural” and “cultural” landscape heritage increasingly recognised worldwide, remote sensing tools are being used more and more to facilitate the recording and management of landscape heritage. The advent of freeware cloud computing services has enabled significant improvements in landscape research allowing the rapid exploration and processing of satellite imagery such as the Landsat and Copernicus Sentinel datasets. This research represents one of the first applications of the Google Earth Engine (GEE) Python application programming interface (API) in studies of historic landscapes. The complete free and open-source software (FOSS) cloud protocol proposed here consists of a Python code script developed in Google Colab, which could be adapted and replicated in different areas of the world. A multi-temporal approach has been adopted to investigate the potential of Sentinel-2 satellite imagery to detect buried hydrological and anthropogenic features along with spectral index and spectral decomposition analysis. The protocol's effectiveness in identifying palaeo-riverscape features has been tested in the Po Plain (N Italy).

Keywords

Multispectral analysis, Sentinel-2, Spectral decomposition, Python, Riverscape, Fluvial and Alluvial Archaeology, Landscape Archaeology, Buried features

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REVISED **Amendments from Version 1**

In this version of the manuscript, we revised both text and illustrations following the reviewers' suggestions. In the Discussion, we added more consideration about the advantages and limits of the FOSS-cloud protocol proposed. The Python script code was updated to provide a plot and histogram for each SI/SD band. Also, now spectral signature values can be interactively extracted by users. Finally, the citation list has been updated with the most recent and helpful scientific literature. We are extremely grateful to the reviewers for their constructive criticism.

Any further responses from the reviewers can be found at the end of the article

Introduction

Toward a definition of "landscape heritage"

Landscapes emerge through complex interrelated natural and cultural processes and consequently encompass rich data pertaining to the long-term interactions between humans and their environments. Over recent millennia, human activities have become progressively more important in shaping geomorphic change[1] to the extent that some scientists argue Earth's history has entered a new epoch, the Anthropocene[2]. In this context, humans are active geomorphological agents, able to modify the physical landscape and shape anthropogenic landscape features[3]. Multi-temporal analysis of landscape dynamics can help identify how human economic development, land use change and population growth have altered natural resources. Past landscape reconstruction enables a better understanding of human resilience to climatic and environmental changes in different periods and locations, and may illustrate examples of sustainable development in the past. At the same time, the analysis of historic land use permits the evaluation of human impact on natural environments[4]. The importance of considering landscape's "natural" and "cultural" heritage values together and promoting interdisciplinary approaches to develop conservation strategies has emerged increasingly strongly over the last decade[5,6]. This interdisciplinary perspective is epitomised in the Council of Europe's European Landscape Convention which defines landscape as 'an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors'. This international treaty lays out pathways towards sustainable development in the landscape based on a balanced and harmonious relationship between social needs, economic activity and the environment. Identifying landscape heritage represents the first crucial phase in any conservation plan[7–9]. In this regard, modern GIS and remote sensing tools have become indispensable tools for landscape research which facilitate the mapping of territories over multiple spatial and temporal scales[10].

GIS and remote sensing in landscape studies: the FOSS-cloud 'revolution'

Geographic information systems (GIS) and remote sensing technologies are increasingly being recognized as effective tools for the documentation and management of valuable natural and cultural landscape features[11,12]. In particular, satellite remote sensing technologies have enabled significant improvements in landscape research and triggered the development of new tools in disciplines including Ecology[13], Geomorphology[14,15] and Archaeology[16–18].

However, GIS proprietary software licenses limit access to broader community growth and implementation, especially in developing nations. Conversely, FOSS (free and open source software) geospatial data and tools represent an invaluable alternative mitigating the need for software licensing and data acquisition, which is a critical barrier to broader participation[10,19,20]. A further step toward more inclusive and borderless access to geospatial research is represented by freeware cloud computing services that enable users to process data and create outputs without significant investment in the hardware infrastructure[21,22]. The two main freeware cloud-based planetary-scale platforms available are the Google Earth Engine (GEE) and the Microsoft Planetary Computer.

The advent of GEE has enabled the rapid exploration and processing of more than 40 years of satellite imagery[23]. GEE combines a multi-petabyte catalogue of geospatial datasets and provides a library of algorithms and a powerful application programming interface (API)[24]. GEE eased the access to publicly available satellite imagery and earth observation tools in many branches of scientific research[23,25–27], revealing new opportunities especially for landscape heritage applications[28]. Amongst others, GEE users can access Landsat (from 1972) and Sentinel (from 2014) datasets. The highest resolution available in GEE (up to 10 m/pixel) is offered by the Copernicus Sentinel-2 satellite constellation, which represents an invaluable free and open data source to support sustainable and cost-effective landscape monitoring[29]. Sentinel-2 carries an innovative wide swath high-resolution multispectral imager (MSI) with 13 spectral bands providing information useful for a wide range of applications such as agricultural and forest monitoring[30,31]. Many studies have considered the potential of Sentinel-2 data in the cultural heritage domain at diverse scales of analysis, from single site up to landscape level[32–34], and as a tool for scientific investigation and heritage management and preservation.

GEE can be employed in several main ways, including i) via the JavaScript API on the web-based IDE Earth Engine Code Editor, or ii) via Python API on local machines. A third option consists of using the Python API in Google Colaboratory (commonly referred to as "Colab")[35,36], a Python development environment that runs in the browser using Google Cloud. The Python API did not originally support any kind of visual output, but this limit has been quickly overcome with the development of new Python modules. Python has proven to be the most compatible and versatile programming language as it supports multi-platform application development. Finally, Python is continuously improved thanks to the implementation of new libraries and modules[37]. Whilst the potential of Python in modelling landscape dynamics has been widely explored[38,39], few publications have so far documented the use of the GEE Python API[40]. In this paper we propose a complete FOSS-cloud approach to detect palaeo-landscape features through the GEE Python API in Colab.

Why riverscapes?

The potential of using the GEE Python API in Colab has been tested in this paper on riverine landscapes for a number of reasons. Human activities have often relied on river systems, whether for agriculture, navigation or trade purposes. Fluvial/alluvial environments have been crucial since prehistory owing to the fertility of alluvial landforms and the availability of water supporting settlement, agriculture, mobility and trade[41]. Archaeological investigations have confirmed that over the last 5000 years human activities have profoundly altered the spatial configuration and rate of fluvial processes, often inducing profound changes to river geomorphology[42]. Riverine landscapes are excellent examples of landscapes which develop through complex relationships between human activities and environmental factors[43–45]. Moreover, the large scale of buried features such as river palaeochannels or ancient canals eases the identification of palaeo-riverscape features using remote sensing. In recent years, remote sensing and satellite imagery have been successfully applied to identify palaeo-geomorphological features (fluvial avulsion, fluvial channels, abandoned meanders, crevasse splays, backswamps) and anthropogenic structures (canals, irrigation systems, artificial levees) in many parts of the world[46–51].

To assess the effectiveness of our FOSS-cloud protocol, northern Italy's Po Plain was used as an ideal test case for the methodology. A huge amount of field- and remotely-sensed geomorphological data are available for the Po Plain and the whole region has been settled and exploited since the Neolithic period. The potential offered by Sentinel-2 imagery has recently been exploited here to map arable land[52]. In this paper we attempt the first Python application of Sentinel-2 data for heritage research in a European riverscape and illustrate the possibility of detecting and interpreting buried anthropogenic landscape features originating in different periods.

Test case area

The Po Plain (Northern Italy) results from the infilling of the depression between the Alps and the Apennines; it is the largest floodplain in Italy. The region forms a natural bridge between the Mediterranean and continental and eastern Europe, and is consequently a key area for understanding environmental and cultural connections between different contexts[53]. People have been closely engaged with fluvial and alluvial dynamics since the region was first colonised and have actively shaped the geomorphology of the basin's rivers since later prehistory.

Geographic and geomorphological background

The Po Plain and its eastward continuation – the Venetian-Friulan Plain – are situated in a transitional region between the Mediterranean and the European continental climate zones (Figure 1). As reported in the Köppen classification, the Po Plain is characterised by a range from humid continental (Cfb) to humid subtropical (Cfa) climate[54]. Intense rainfall (700–1200 mm

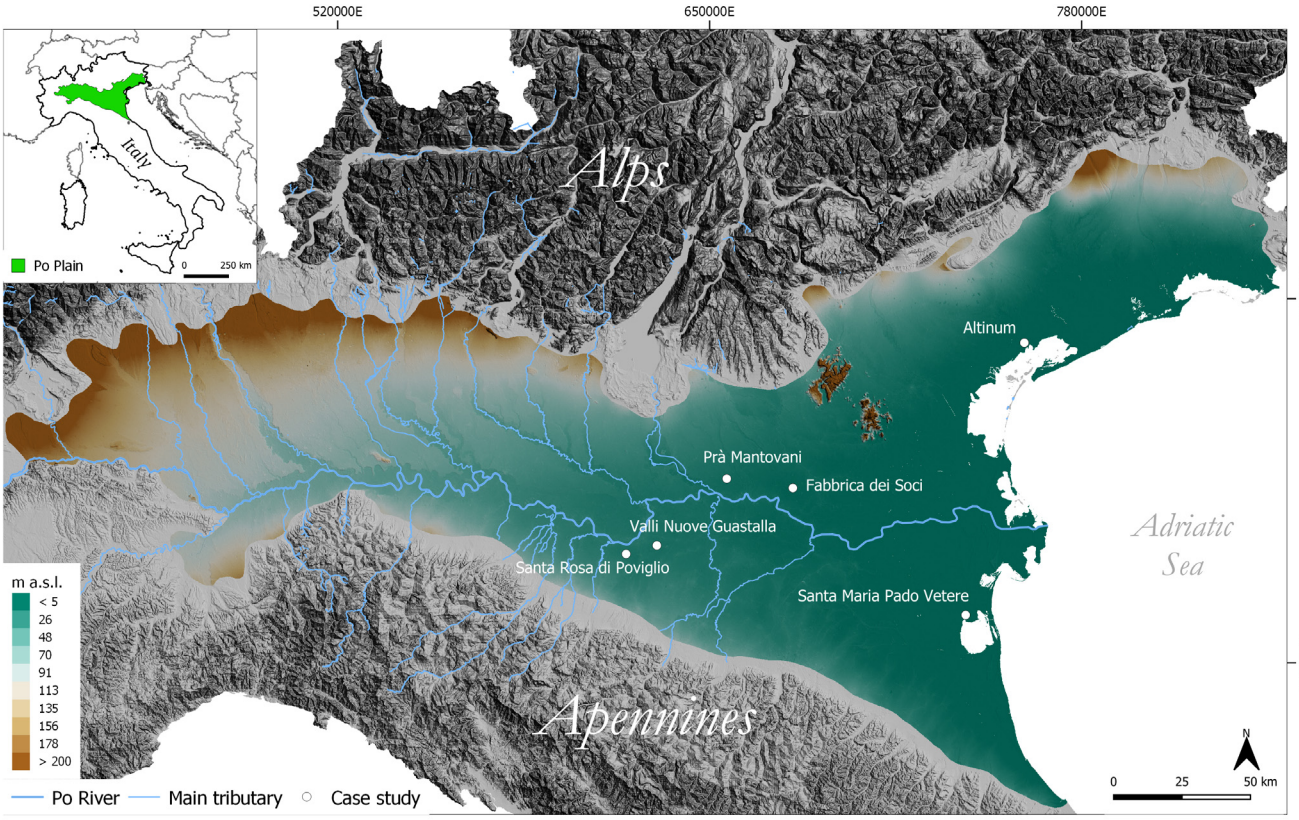


Figure 1. Schematic representation of the test case area.

per year) occurs throughout the year and the seasonal pattern of precipitation strongly influences the annual regime of the Po River[55]. The highest rainfall is reached in spring and autumn while the lowest precipitation is usually registered in January and summer (June and July)[56]. Peaks in the Po River discharge volumes are usually observed in late spring, likely due to melting snow from mid-altitude mountains[57].

The high levels of relative humidity are a consequence of the specific physiography of the plain, surrounded by the Alps and the Apennines, and the influence of the Adriatic Sea[58,59] (Figure 1). The geomorphological characteristics of the northern and southern sides of the plain differ profoundly[60,61].

The area along the foothills of the Alps is characterized by the presence of Quaternary glacial amphitheatres[62,63] in front of which fluvial fans slowly degrade southwards and eastwards. The fans are interpreted as a result of the mobilisation of glacial and fluvioglacial sediments by rivers which have formed an outwash plain over time[64]. Different phases of alternating depositional and erosional events have resulted in the formation of terraced landforms along the outwash plains. The southern portion of this area consists of a succession of fluvial terraces shaped by the Po River and its tributaries and dating from the Upper Pleistocene to the Holocene[65,66]. Moving eastward, a large portion of the Po Plain and the Friulan-Venetian Plain were built by aggradation processes during the Last Glacial Maximum (LGM, ~22ka - 16ka years BCE)[67,68]. After that phase the Alpine tributaries of the Po River underwent a dramatic phase of incision that caused the formation of terraces and a downstream shift in deposition zones[69]. On the opposing, southern side of the Po Plain, the Apennine watercourses developed an apron of fluvial mega-fans along the boundary of the floodplain. A well-preserved system of Late Pleistocene to Holocene alluvial fans extends northward between the Apennine foothills and the Holocene plain[70,71]. The distal part of alluvial fans presents a telescopic shape resulting from alternating aggradation/entrenchment phases tuned by Holocene climatic changes. Each aggradational cycle triggered an incision at the top of the pre-existing fan and the progradation of a new fan in a more distal position[72]. Finally, during the Late Holocene, the aggradation of riverbeds resulted in channel diversions and frequent inundation of flood-prone areas[73]. Additionally, in the eastward portion of the Po Plain and in the Venetian–Friulian area the Late Quaternary floodplain evolved in response to the climate-controlled development of alluvial systems and sea-level changes[74–76].

Environmental history and human settlements

Thanks to its complex settlement and land-management history, the Po Plain represents an ideal setting to assess the potentiality of our FOSS-cloud approach to detect riverscapes' palaeo-features.

Since the Mid-Holocene (~5–3ka BCE), Neolithic communities settled at an increasing rate in the Po Plain owing to its suitability for agriculture[77]. During the Bronze Age (~1700 – 1150 BCE), the Po Plain witnessed the emergence of proto-urban civilizations – the Terramare culture – that altered the natural fluvial landscape, introducing the earliest systems for hydraulic management of the fluvial network and extensive woodland clearance[78–80]. Deforestation and farming development heightened during the Iron Age (~1100–700 BCE) – the Etruscan period – when agricultural activities became the major land use and farmers the key agents in modifying the landscape[81,82]. Between the 2nd-1st century BCE, the Po Plain was modified significantly following Roman colonisation, with the introduction of the centuriation system for agricultural management which entailed the creation of a regular grid of roads, ditches and fields. In this phase, at least 60% of the surface of the Po Plain was deforested and converted into farmland[83]. From the 5th century CE, a lack of maintenance of irrigation networks which may have been linked to political disruption associated with the end of the Roman Empire[84], combined with surface instability triggered by a cool climate phase[85], meant that large portions of the Po Plain changed into wetlands[70]. This progressive waterlogging process endured until the beginning of the 10th century CE with significant implications for settlement and farming practices[86]. Between the 10th and 14th centuries CE – corresponding to the Medieval Warm Period[85]– land reclamation intensified owing to an increased demand for arable land alongside general population growth in Europe[87]. At the beginning of the 12th century CE wetland reclamation, the construction of levees and canalisation increased and a series of canals were constructed in the Po Plain for irrigation and navigation[88,89]. In the Renaissance, extensive land and water management activities advanced the process of land reclamation in many coastal and interior wetlands[73,90]. During the Little Ice Age (~1500–1850 CE ca.) deforestation accelerated and reached its peak in the late 1700s, while the construction of embankments was completed during the 19th century CE[85]. Flood defences and drainage systems were further reinforced during the 20th century to reduce the risk of inundation[91]. Human water/land management and natural resource exploitation (e.g. deforestation and quarrying) have been so widespread over the centuries that only a tiny portion of this riverscape can be considered completely 'natural' today[83].

Material and methods

The first application of GIS and remote sensing techniques to record the past landscape settings of the Po Plain dates back to the end of the nineties[92]. Today, significant improvements in FOSS software and the increased availability of open-source satellite datasets enable the development of more efficient remote sensing approaches.

The mosaic of cultivated fields on the Po floodplain is subject to frequent changes which can make uniform visual analysis difficult[50]; this heterogeneity can also complicate the detection of past riverscape features, as the factors that influence it (crop types, seasonal rainfall, soil moisture) vary in areas with different environmental conditions. For example, variations in the capacity to retain soil moisture are a major factor precluding or enhancing the detection of ancient hydrological features[34,93]. Multi-temporal datasets have the capacity to include diverse land-use/land-cover (LULC) scenarios enabling identification of features that may not be visible on individual images during a particular period of the year[50].

Sentinel-2 dataset

The Sentinel-2 (S2) satellite constellation was developed by the European Space Agency (ESA) in the framework of the European Commission Copernicus Programme. The twin satellites (A and B) of the S2 programme have a 5-day temporal resolution and their multispectral sensors acquire data in 13 separate bands with a spatial resolution up to 10 m (Table 1). In this paper we utilize the GEE dataset S2 MSI (MultiSpectral Instrument), Level-1C orthorectified top-of-atmosphere (TOA) reflectance (dataset availability: June 2015 - present) filtered with the cloud masking quality assurance band QA60.

Buried natural palaeochannels and human structures result in crop marks and soil marks on the surface because they retain a different amount of moisture compared to the surrounding soil[94]. The identification of crop/soil marks from aerial imagery has informed the identification of buried archaeological sites since the 1920s[95–97]. Satellite multispectral images can be more effective in this respect than traditional aerial photography and researchers have identified key bands for the detection of palaeo-landscape features: visible (0.4 – 0.7 μm), near infrared (NIR) (0.7 – 1.4 μm), and short-wave infrared (SWIR) (1.4 – 3 μm)[32,98,99].

Even with the high resolution of modern satellite sensors[100], the detection of crop marks is often affected by several issues, the most important being the phenological stage of the crops[101,102]. The heterogeneity of the Po Plain farmland and high annual precipitation rates further complicate the recognition of crop marks in the area. Meanwhile soil marks can appear on bare soil as colour changes, easily identifiable after ploughing: differences in soil colour in ploughed farmland highlight traces of past features whether positive (e.g. damper, wetter material from a palaeochannel or former ditch) or negative (e.g. buried natural or artificial levees)[16]. In the case of the Po Plain previous studies[103–105] suggested that buried features are likely to be more visible in soil marks after ploughing. Moreover, as highlighted in similar methodological studies, archaeological features tend to be more often visible on bare soil than in cultivated fields in S2 satellite imagery[34].

Nevertheless, variations in local weather conditions or agriculture processes mean buried features appear in different ways in images acquired at different times. This problem applies to satellite (or aerial) imagery and can lead to negative impacts on the detection of crop or soil marks.

To help overcome this issue and to optimize the visibility of palaeo-features, this study adopted a multi-temporal approach[50,102] by calculating the mean values of bands in the most promising periods for the identification of crop/soil marks between the years 2015 – 2020.

In the test case area the choice of timespan was driven by two specific environmental factors. The first is related to the increase in intensity and frequency of drought episodes in the Po Plain in the last decade[56]: the longest recorded period of drought lasted from October 2016 to November 2017 (Figure 2). As noted above, changes in soil moisture retention tends to facilitate the detection of crop/soil marks especially in severe drought periods.

Table 1. S2 Satellites bands properties. (https://sentinel.esa.int/web/sentinel/technical-guides/sentinel-2-msi/msi-instrument).

Name	Pixel Size	Wavelength	Description
B1	60 meters	443.9nm (S2A) / 442.3nm (S2B)	Aerosols
B2	10 metres	496.6nm (S2A) / 492.1nm (S2B)	Blue
B3	10 metres	560nm (S2A) / 559nm (S2B)	Green
B4	10 metres	664.5nm (S2A) / 665nm (S2B)	Red
B5	20 metres	703.9nm (S2A) / 703.8nm (S2B)	Red Edge 1
B6	20 metres	740.2nm (S2A) / 739.1nm (S2B)	Red Edge 2
B7	20 metres	782.5nm (S2A) / 779.7nm (S2B)	Red Edge 3
B8	10 metres	835.1nm (S2A) / 833nm (S2B)	NIR
B8A	20 metres	864.8nm (S2A) / 864nm (S2B)	Red Edge 4
B9	60 metres	945nm (S2A) / 943.2nm (S2B)	Water Vapor
B10	60 metres	1373.5nm (S2A) / 1376.9nm (S2B)	Cirrus
B11	20 metres	1613.7nm (S2A) / 1610.4nm (S2B)	SWIR 1
B12	20 metres	2202.4nm (S2A) / 2185.7nm (S2B)	SWIR 2

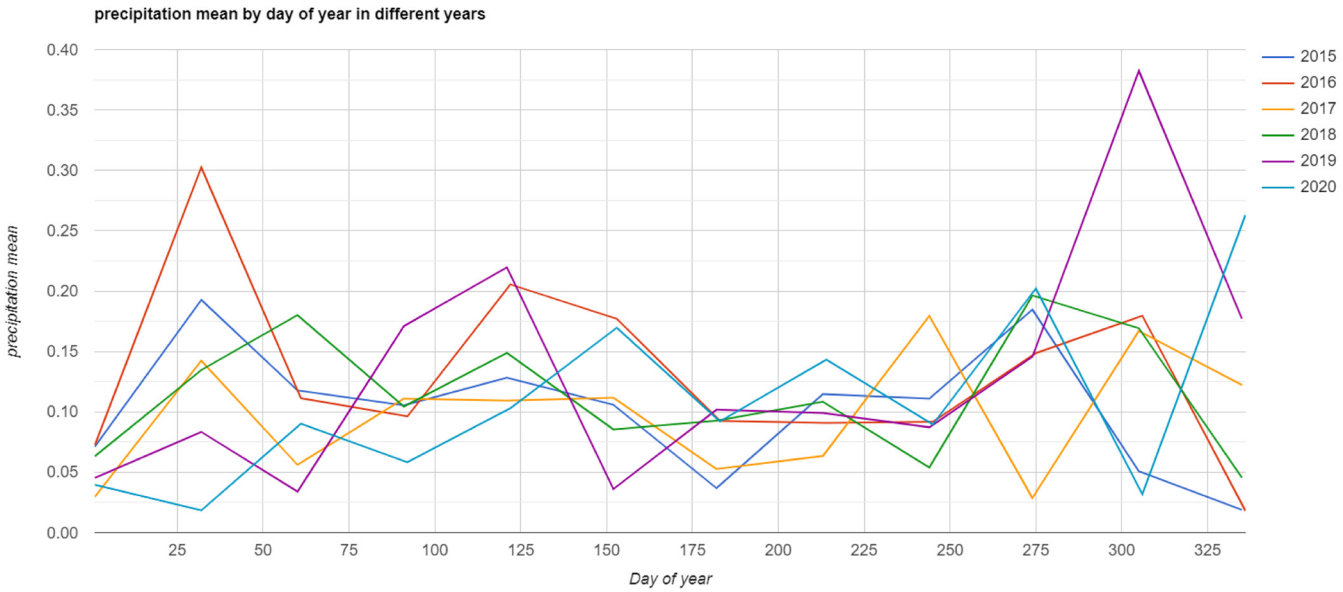


Figure 2. Annual mean precipitation rate between 2015 and 2020 in Po Plain. Source: Monthly Global Precipitation Measurement (GPM) v6. Plot generated in Google Earth Engine.

Secondly, autumn, winter and early spring are periods of relatively uniform land cover in the Po Plain[104]: ploughing takes place across large areas of arable land, rice paddy fields have not yet been inundated and other winter crops have not yet reached their maximum growth (Figure 3). Focusing on the low-vegetation period of the year the general uniformity in the land cover helps to mitigate the problems of field mosaicking, easing the detection of buried features.

Furthermore, looking at the average annual performance of S2 bands, 150 - 270 days of the year (DoY) show a general lower average bands reflectance than other seasons: this is likely due to the fact that vegetation strongly absorbs radiation and the resulting reflectance is generally low[106] (Figure 4).

The annual average vegetation cover and spectral reflectance helped in choosing the multi-temporal timespan that corresponds to two low vegetated periods (30 – 120 and 270 – 360 DoY) of each year from 2015–2020. The resulting image collections are merged and reduced in a single image. In other words, this workflow generates a single composite image for the entire analysis period containing six S2 bands (B2, B3, B4, B8, B11 and B12, see Table 1).

The choice of timespan is the only part of the protocol that needs to be customised by users according to the peculiar environmental conditions of each study area. In our test case area no preliminary bands sensitivity test[33] has been performed. This was beyond the scope of the current paper, whose the main goal is to evaluate the potential and limits of this cloud protocol as an alternative remote sensing FOSS-tool for mapping buried landscape features. Pre-existing literature about the occurrence of buried natural and anthropogenic features in the Po Plain provided a valuable set of benchmarks for evaluating the effectiveness of the method.

The S2 satellite data were accessed through the Python module `geemap`[107] in Colab[35], a serverless Jupyter notebook computational environment for interactive development. The native GEE Python API has relatively limited functionality for visualizing results but the `geemap` Python module was created specifically to fill this gap. The Python code developed enables the analysis of the S2 filtered image collection through spectral index (SI) and spectral decomposition (SD) techniques. Each image was exported in Geo.TIFF format in QGIS where the min/max values were adjusted with the cumulative count cut tool. Finally, the figures presented in this paper were generated in the QGIS layout editor. The Python module `rasterio`[108] was used to create individual plots for each band of the raster. Additionally, the Python packages `rioxarray` and `matplotlib`[109] were employed, respectively, to access each raster band and create customisable histograms of their values. (Figure 5).

Spectral indices

SIs for remote sensing purposes consist of mathematical combinations of different bands to enhance particular environmental characteristics. Their use is common in different fields of research, for example in monitoring variations in snow and glacier cover or in disaster prevention and management[110].

In this study, multi-temporal red-green-blue (RGB) colour composites were used to generate two different compositions: RGB (bands 4-3-2), and false short wave infrared colour (FSWIR, bands 12-8-4). RGB provides a true-colour visualization, very

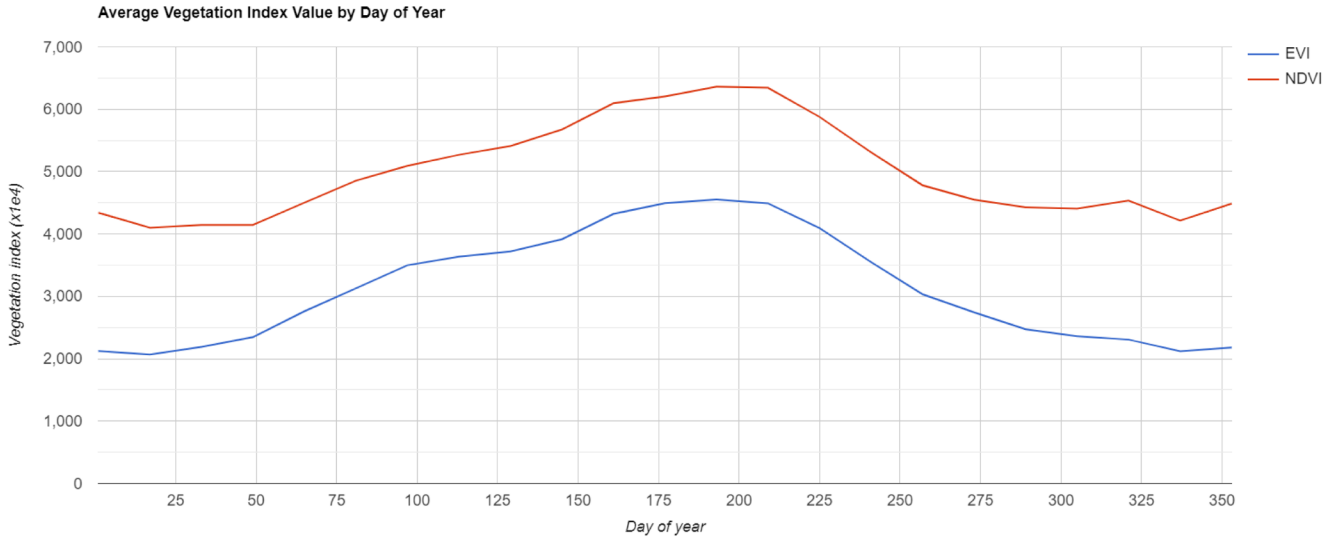


Figure 3. Average Vegetation Index Value by Day of Year between 2015 and 2020 in Po Plain using Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI). Source: MOD13A1.006 Terra Vegetation Indices 16-Day Global 500m. Plot generated in Google Earth Engine.

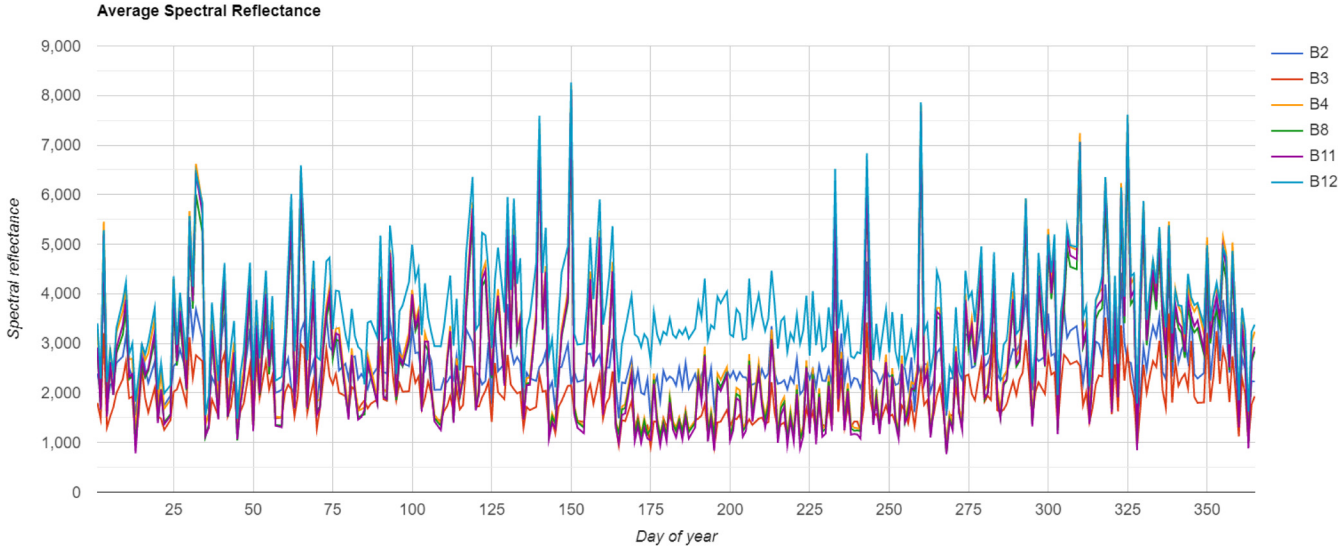


Figure 4. S2 Average Spectral Reflectance by Day of Year between 2015 and 2020. Plot generated in Google Earth Engine.

similar to the human colour perception, while false-colour images enable the identification of areas with different reflectance response to enhance the visibility of anomalies.

Spectral indices that combine NIR and red channels generally increase the visibility of crop- and soil-marks. Vegetation indices (VIs) have been widely tested to detect buried structure and fluvial palaeochannels[34,50,99,101,111]. In particular, Agapiou *et al.*[98] reformulated the NDVI (normalized difference vegetation index) to elaborate a specific VI for the identification of archaeological remains: the normalized archaeological index (NAI). Focusing on the low-vegetation period of the year, this study adopted spectral indices that could potentially enhance the detection of soil marks including the bare soil index (BSI). The BSI combines blue (B2), red (B11), NIR (B8), and SWIR 1 (B4) spectral bands to capture soil variations[112] according to the formula: $((red + SWIR\ 1) - (NIR + blue)) / ((red + SWIR\ 1) + (NIR + blue))$.

The SWIR and the red bands are employed to quantify the soil mineral composition, while the blue and the near infrared spectral bands enhance the vegetation. In general, the SWIR spectral range is strongly sensitive to soil moisture content

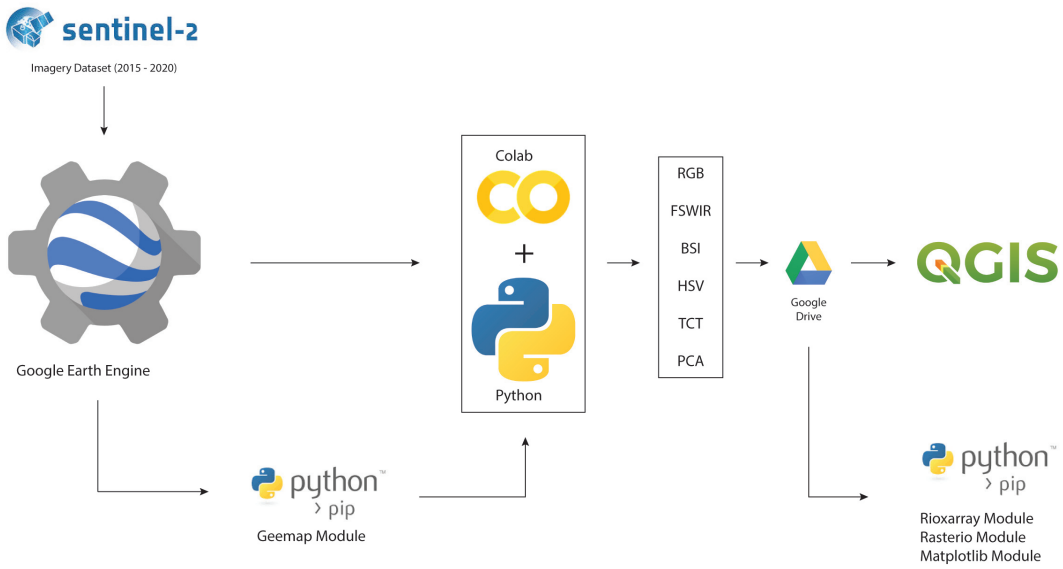


Figure 5. Free and open-source software (FOSS) methodological approach adopted in this research. RGB: Red-Green-Blue colour composite; FSWIR: False colour composite; BSI: Bare Soil Index; HSV: Hue, Saturation and Value; TCT: Tasselled Cap Transformation; PCA: Principal Component Analysis.

enabling the detection of moisture variations in space and time[16]; recent research suggests the SWIR2 band may be valuable for calculating BSI because it seems more sensitive in terms of classification accuracy[113]. For this reason, the SWIR2 band was used in this study to calculate both FSWIR and BSI indices.

Spectral decomposition

Three different spectral decomposition (SD) techniques were used in this study: hue, saturation and value (HSV), tasselled cap transformation (TCT) and principal component analysis (PCA). HSV, TCT and PCA have been successfully employed to detect both archaeological structure and past fluvial features in different environmental contexts[34,50,114]. Here these three SD approaches were tested to detect past riverscape features in continental environmental conditions.

Hue, saturation and value (HSV). HSV (hue, saturation, value, also known as HSB or hue, saturation, brightness) is an alternative representation of the RGB colour space. In HSV SD, Hue (H) defines pure colour in terms of red, green and blue, Saturation (S) specifies the purity of a colour relative to gray, and value (V) refers to the brightness of the colour. HSV performs a rotation from the RGB axis and it is characterized by the three relevant properties: 1- nonlinearity, 2- reversibility and 3 - independence of each component from the others[16]. In our Colab Python script code, we calculate HSV through the GEE method `.rgbToHsv()`.

Tasselled cap transformation (TCT). The TCT, known also as Kauth-Thomas technique[115], was developed for enhancing spectral information content of satellite data. The TCT consists in a transformation of the original images into a new data set obtained by linear combinations of the original bands. This SD technique is performed on a pixel basis to better represent the underlying structure of the image according to the formula:

$$TC = (WTc)(DN) + B$$

where *WTc* stands for weighted transforming coefficient (i.e. specific transformation coefficients statistically derived from images and empirical observations), *DN* for digital number and *B* for bias. The transformation *WTc* depends on the sensor considered, because different sensors have different numbers of bands which, in turn, have different spectral responses[16]. There are three composite variables of TCT bands which are routinely adopted: *brightness* (TCTb, measure of bare soil), *greenness* (TCTg, measure of vegetation), *wetness* or *yellowness* (TCTw, measure of soil and canopy moisture)[116]. To calculate the TCT bands for S2, the WTcs recently defined by Shi and Xu[117] were adopted for their better performance than previous proposed coefficient indexes[118,119]. Finally, in Colab, we computed the TCT components with the `ee.Array` type utilising the Sentinel-2 TCT Coefficients for the 6-Band Image (blue, green, red, NIR, SWIR1, SWIR 2) (Table 2).

Principal component analysis (PCA). The PCA transform (also known as the Karhunen-Loeve transform) consists of a linear transformation which decorrelates multivariate data by rotating the axes of the original feature space and outputs uncorrelated data[120]. PCA reduced the dimensionality of the data, providing a new series of less correlated bands, limiting the loss of information and enhancing the features of interest[16,34]. In the Python script code the PCA is calculated by diagonalizing the input band correlation matrix through Eigen-analysis (`eigen()`).

Table 2. WTcs for S2 defined by 100.

TCT bands	S2 WTcs
TCTb	0.3510 BLUE + 0.3813 GREEN + 0.3437 RED + 0.7196 NIR + 0.2396 SWIR 1 + 0.1949 SWIR 2
TCTg	-0.3599 BLUE -0.3533 GREEN -0.4734 RED + 0.6633 NIR - 0.0087 SWIR1 -0.2856 SWIR2
TCTw	0.2578 BLUE + 0.2305 GREEN + 0.0883 RED + 0.1071 NIR -0.7611 SWIR1 -0.5308 SWIR2

Results

To assess the potential of the FOSS - cloud procedure discussed in this paper, the Python script code was tested at different locations in the Po Plain with well-known archaeological sites. The key points selected to test the script code consist of well-documented areas where anthropogenic activities have altered the pristine alluvial and fluvial geomorphological settings since protohistory. The case studies (from west to east) are: *Terramara Santa Rosa di Poviglio* (RE), *Valli Nuove di Guastalla* (RE), *Pra' Mantovani* (MN), *Fabbrica dei Soci* (VR), *Santa Maria in Pado Vetere* (FE) and *Altinum* (VE) (Figure 1).

Santa Rosa di Poviglio

The site of Terramara Santa Rosa di Poviglio is a key settlement associated with the Bronze Age Terramare Culture (TC)[121]. The village and its surroundings were delineated through an artificial modification of a pre-existing crevasse splay lobe. The settlement consists of two moated villages delimited by earth ramparts connected to an adjoining river channel through a canal network[122,123]. The earth ramparts are easily visible in all the SI and SD analysis performed as shown in Figure 6. The soil marks corresponding to the two moated villages are particularly evident in the FSWIR and BSI compositions while RGB, HSV and PCA images highlight the presence of a palaeochannel that flows southwards from the TC site. A square-shape feature lies near the southern limit of the Bronze Age village and corresponds to a Roman structure related to the centuriation of the surrounding landscape[124].

Valli Nuove Guastalla

This site lies in the Central Po Plain, not far from the Terramara Santa Rosa di Poviglio site, in a portion of the floodplain known as "backswamp". This geomorphological terms refers to the lowest area of floodplains, poorly drained, where finer sediments accumulate after flooding events[42]. As noted above, the period which witnessed the collapse of the Roman Empire was also associated with climatic instability and progressive waterlogging of the Po Plain. The Roman farmland of the backswamps was inundated and became a palustrine environment[73]. Valli Nuove Guastalla is a good location to investigate the impact of the processes which occurred between the Roman and the Medieval eras even though the cultivated mosaic of fields precludes clear visibility of crop/soil marks here (Figure 7). In the RGB image calculated from the S2 seasonal mean values three buried orthogonal axes are barely visible, remnants of the drainage system created through Roman centuriation. These palaeofeatures are slightly visible also in the FSWIR and PCA images although hardly recognisable in the others: this condition is due mainly to the S2 image resolution as treated in detail in the Discussion. Buried canals and palaeochannels are highlighted in the FSWIR, HSV and PCA images: these features are most likely the results of flood management during Medieval land reclamation activities in the area[73].

Pra' Mantovani

The environmental context of the Pra' Mantovani sites is similar to Valli Nuove di Guastalla. Here, recent archaeological surveys[125,126] have registered the presence of Medieval settlements and buried Roman ditches. In all the SI/SD of Figure 8, an Early Medieval motte is clearly visible almost in the middle of the area. In the surroundings of this archaeological feature, a series of palaeochannels can be recognised. Positive crop and soils marks in the RGB and PCA images highlight irregular rounded features that have been interpreted as buried archaeological structures[125,126].

Fabbrica dei Soci

This site is one of the most important TC settlements in the Po Plain. In all the SI and SD images the general pattern of the site and the area nearby is clearly detectable (Figure 9). The Terramara Fabbrica dei Soci presents a regular square-shaped village centred in a complex hydraulic system that distributed the water diverted from a river palaeo-channel in the surrounding fields for irrigation[103]. The water management documented at this site can be considered as paradigmatic for the whole TC[104,127,128]. Moats, canals and palaeochannels are especially recognisable in the RGB, FSWIR and PCA images. In the HSV image, the shape of the buried palaeochannels is particularly legible, while in the TCT the square-shaped settlement stands out clearly.

Santa Maria in Pado Vetere

Santa Maria in Pado Vetere consists of an Early Medieval church located in the area of the former palustrine environment known as *Valli di Comacchio* (FE). These backswamps were completely reclaimed during the 20th century CE[129,130]. The land reclamation works unearthed several archaeological sites, in particular the Etruscan harbour of Spina[131,132], Roman villas and the early Medieval church of Santa Maria[133–135]. The place name " *in Pado Vetere*" derives from the latin " *Padus Vetus*" and indicates the presence of a Po River palaeochannel. This palaeo-riverscape feature is clearly visible in all the SI/SD images (Figure 10) crossing the area from NW to SE. That course of the Po River flowed close to the Santa Maria church. Buried artificial canals are connected to the *Padus Vetus* and were probably used for

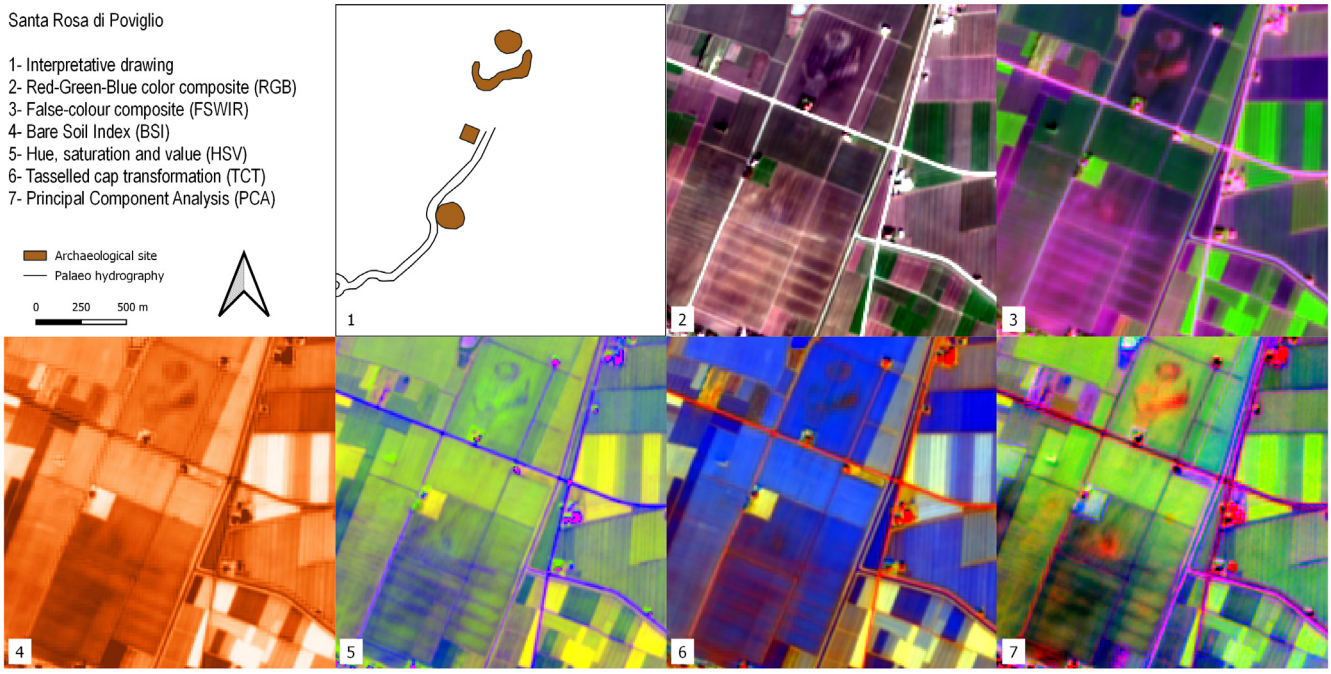


Figure 6. Outputs of the Terramara Santa Rosa di Poviglio site.

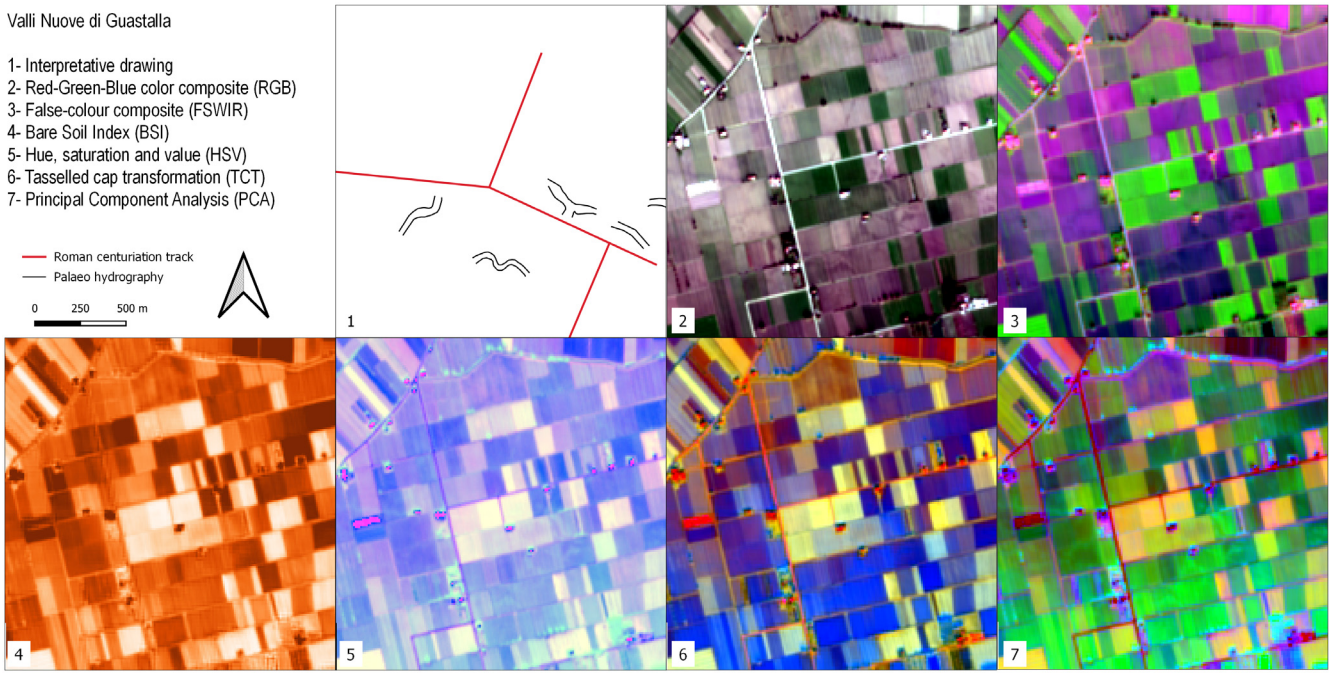


Figure 7. Outputs of the Valli Nuove di Guastalla site.

navigation and irrigation purposes. The archaeological area of Spina and the Santa Maria church cemetery are hardly recognisable due to the resolution of the S2 imagery (see Discussion). In all the images, buried Holocene coastlines are easily detectable[135,136]. In the southern sector of the area the highly fragmented pattern of the farmland here precludes the visibility of the Po River palaeochannel and all other buried features: a similar situation was observed in the Valli Nuove di Guastalla.

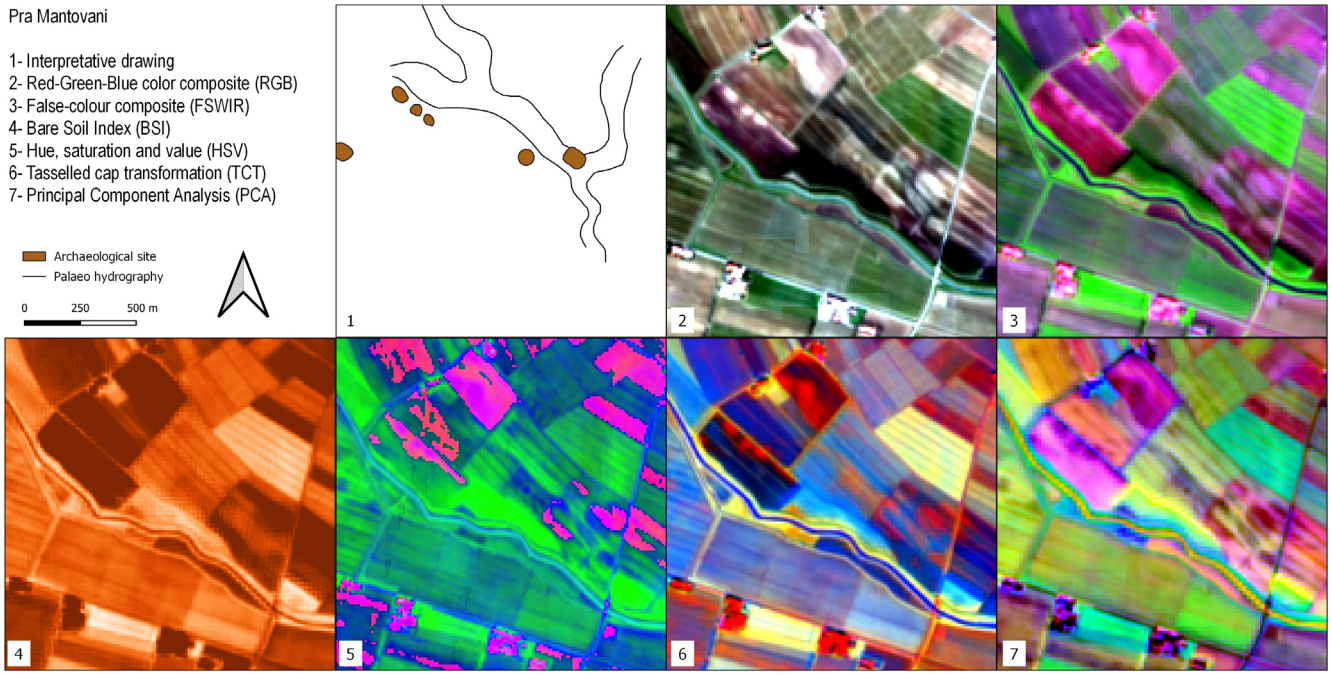


Figure 8. Outputs of the Pra' Mantovani site.

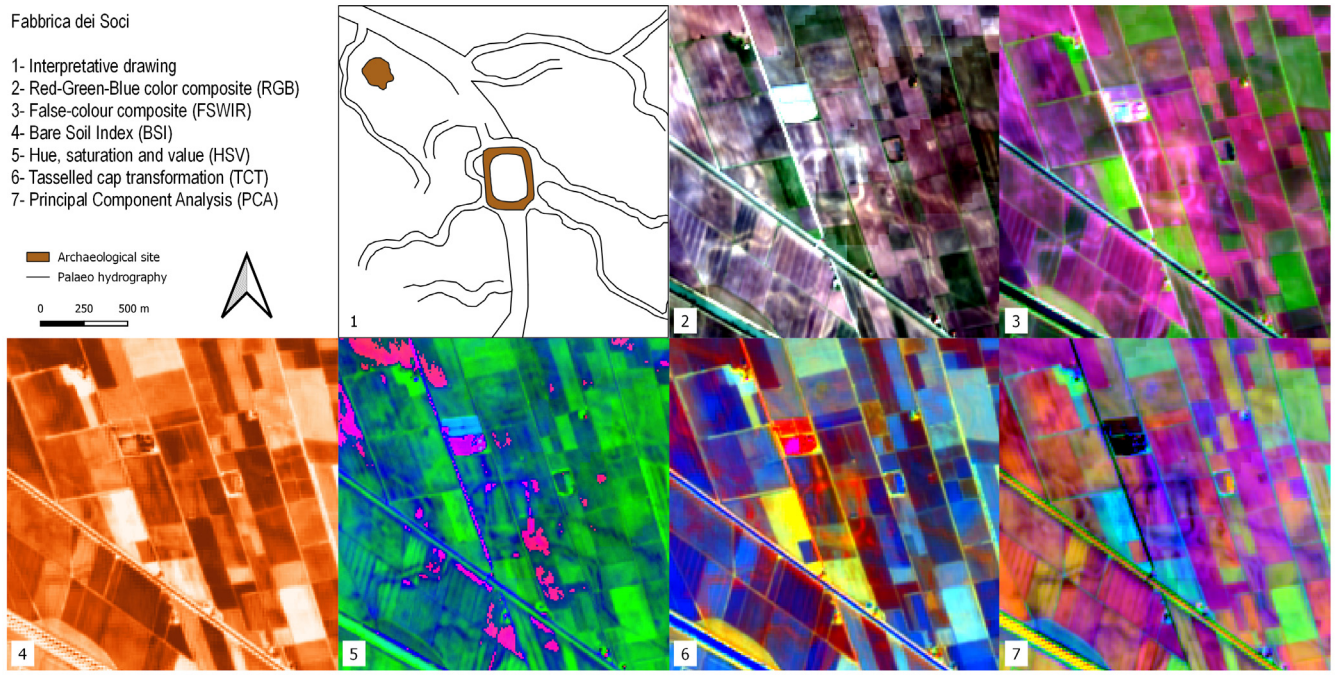


Figure 9. Outputs of the Fabbrica dei Soci site.

Altinum

Altinum was a Roman harbour on the inner margin of the Lagoon of Venice founded in the 1st century BCE. Its inhabitants colonized the northern lagoon islands in the 5th century CE and created the earliest settlement at Venice. This site was particularly suited for testing the Python script code because the features detected could be compared with the results of a study that reconstructed the urban topography and palaeoenvironmental setting of Altinum using high - resolution near-infrared (NIR) aerial photographs[137]. Traces of buried hydrological features are visible in the area near the Roman city. Canals and roads are the only elements of the Altinum urban topography that can be detected

with our FOSS-cloud protocol: as mentioned above, this limit is related to the resolution of the S2 bands. (Figure 11).

Discussion

The outputs generated for the test locations of the Po Plain show some of the potentialities and limits of the GEE Python API in Colab as an alternative remote sensing tool to identify buried natural and anthropogenic palaeo-riverscape features.

As noted previously, to identify the best period of visibility it is crucial to take into consideration crop rotation and meteorological conditions in the region of interest. In our test area the choice was particularly strategic because the autumn and winter/early spring seasons are characterised by a low vegetation and relatively uniform land cover (Figure 3 and Figure 4). Moreover, the detection of crop/soil marks is strongly related to the soil moisture retention of buried features. In this regard, the S2 image

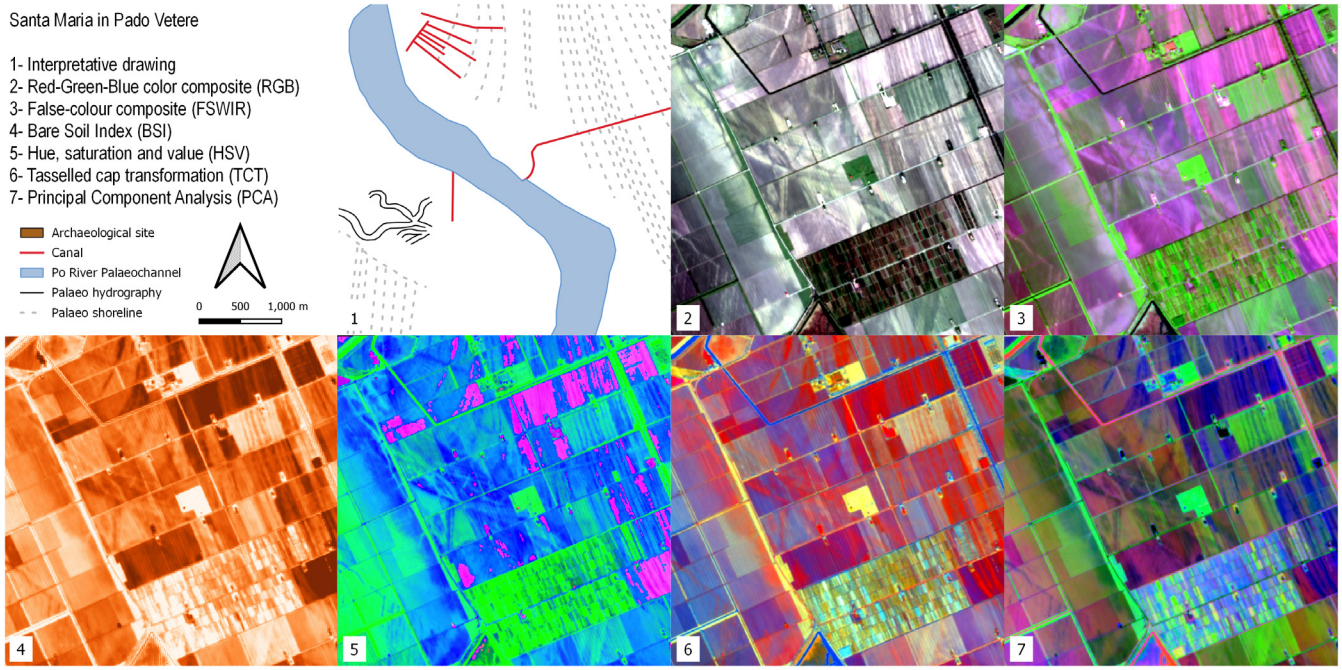


Figure 10. Outputs of the Santa Maria in Pado Vetere site.

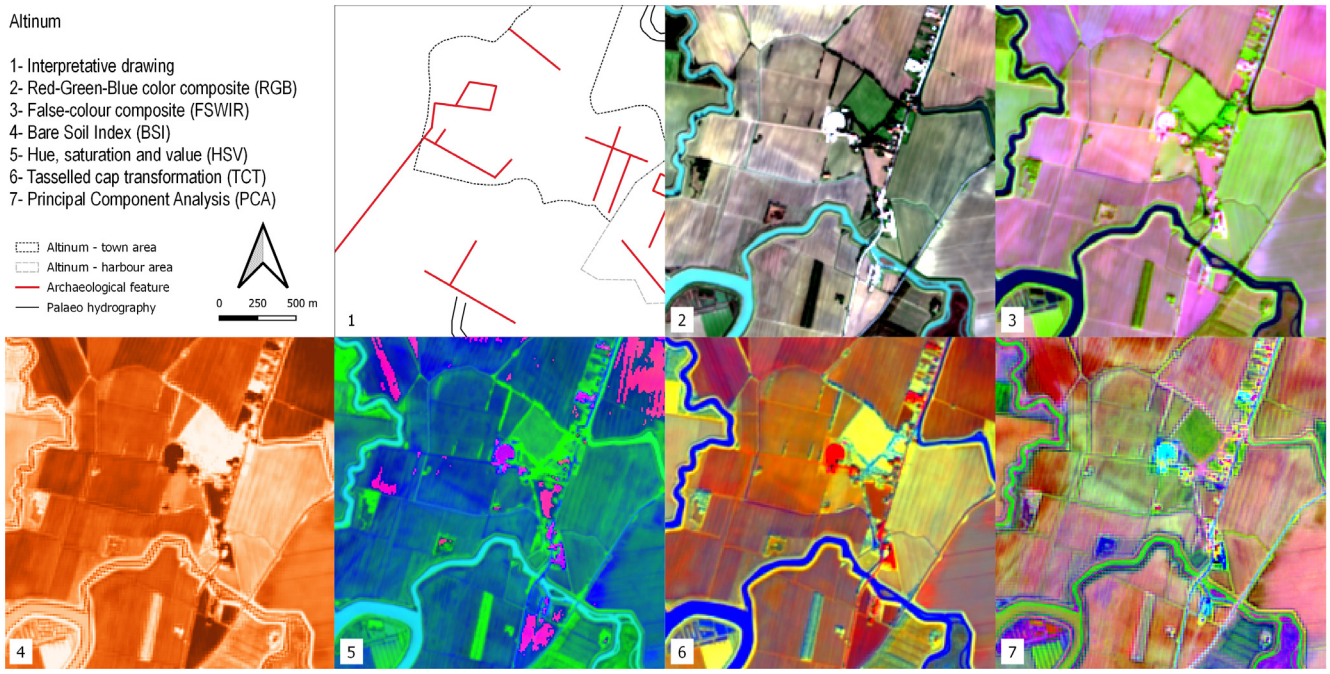


Figure 11. Outputs of the Altinum site.

collection selected includes severe drought events (e.g. years 2016 and 2017) alternated with higher precipitation rate periods (e.g. year 2018) (Figure 2); this alternation of high and low rainfall intensity seems to have positively affected the calculation of the mean values of multitemporal bands for the identification of crop/soil marks. As we expected, the period selected to perform the multitemporal analysis proved fruitful in terms of detection of crop and (especially) soil marks. As known from the literature[103–105], buried features (both natural and archaeological) appear to be more visible on bare soil than in cultivated fields, especially in highly mosaicised farmland. In the test area this eventuality was observed especially in the cases of Valli Nuove di Guastalla (Figure 7) and Santa Maria Pado Vetere (Figure 10).

The Inspector and Plotting tools of the `geemap` Python module enable the extraction of spectral signature value of pixels interactively. Basically, users can sample spectral values directly on the displayed outputs. For example, Figure 12 shows the application of these tools in the Fabbrica dei Soci site (Figure 9). The analysis of the spectral signatures between the buried palaeo-features and neighbouring area shows significant differences in the B11 (SWIR 1) and B12 (SWIR 2) values.

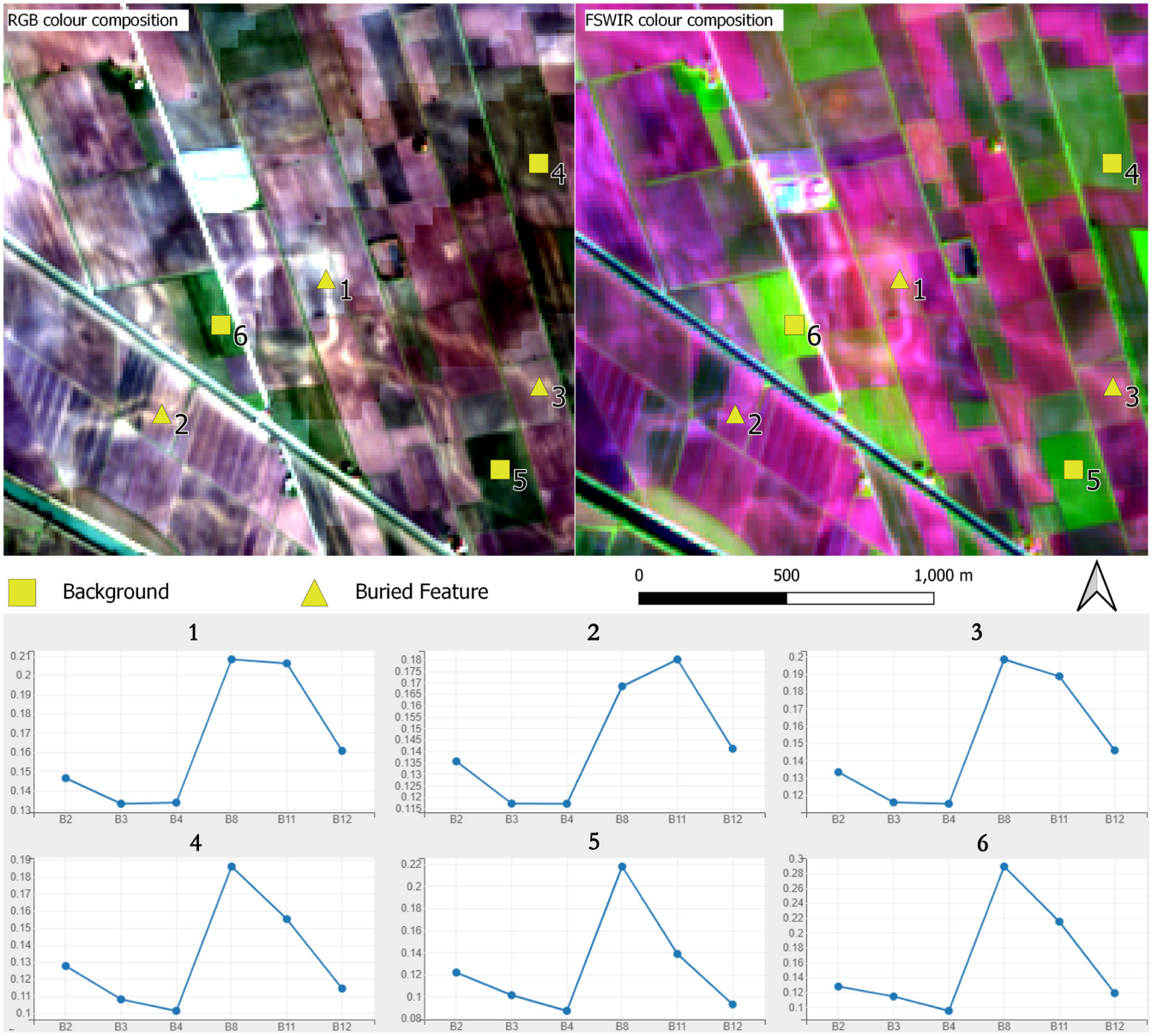


Figure 12. Fabbrica dei Soci site: spectral signature of individual Sentinel-2 bands sample in correspondence of paleo features and in the neighbouring background.

As the literature shows[16,113], the SWIR spectral range is strongly sensitive to soil moisture content easing the detection of moisture variations: in our test area SWIR bands seem particularly effective in the detection of buried palaeo-features.

The second part of the protocol enables the user to obtain plots and histograms for each output band. It is worth highlighting the usefulness of plotting each band of all outputs separately to compare the performance of single bands in the identification of crop/soil marks. In the example of Fabbrica dei Soci, Figure 13–Figure 17 show how some bands seem to offer a greater contrast between the palaeo features and the neighbouring spaces than the compositions/combinations, aiding the identification of buried elements. However, the visibility of these features is always dependent on several elements, and this may vary in other case studies. Moreover, histograms show the frequency distribution of the digital number (DN) values of each band, enabling a preliminary overview about the general performance of each output.

Looking at the singular band plot for the Fabbrica dei Soci site (Figure 13), crop/soil marks seem particularly evident in the B4 and in the B8 plot even if significant differences in the B11 (SWIR 1) and B12 (SWIR 2) values have also been shown (Figure 12). This is probably due to the higher resolution (10 m) of the B4 and B8 bands compared to the SWIR bands (20 m) (Table 1).

The BSI index plot and histogram (Figure 14) return no significant information about the overall performance of this output in the identification of related crop/soil marks: as mentioned above, the choice of this spectral index was not particularly fruitful to visualise buried palaeo-features except for TC buried structures such as moats and the village perimeter (Figure 6 and Figure 9).

In, the HSV output the *Saturation* band returned the clearest visualisation of buried features (Figure 15). As noted above the HSV consists of an alternative representation of the RGB colour space and vivid colours tend to be highly saturated while low saturation characterises pale colours.

TCT and PCA were suitable for the identification of riverscape palaeo features in RGB combination. TCT was derived by the composition of TCTb, TCTg and TCTw bands and it was effective in the identification of positive crop/soil marks. In the *Brightness* band (TCTb, measure of bare soil), buried features are particularly visible, while they are barely recognizable in the *Greenness* (TCTg, measure of vegetation) and *Wetness* (TCTw, measure of soil and canopy moisture) bands (Figure 16).

The detection of the palaeohydrography was much evident in the PCA obtained by the combination of the 1st, 2nd and 3rd principal components. PCA appears to be the most promising method adopted in this research along with the RGB and FSWIR SI composition. PCA outputs returned a detailed image of the riverscape palaeo-features in all the key points, considering that the first two or three principal components encompass nearly 80%–90% of the original data's variance[138]. Thanks to their capacity of reducing redundant information and highlighting variance for the recognition of individual elements, if we plot the PCA's bands separately, some principal components depict a significant contrast between the background and the palaeochannels and buried canals which, in turn, substantially eases the detection of these features[139] (Figure 17).

Considering the possible reproducibility of the method presented here, the main advantages of this FOSS-cloud protocol are not only limited to mitigating the need for specialist software and data licensing (thereby enabling a broader participation in the use of geospatial tools). One of the additional positive technical aspects of using the GEE Python API in Colab relates to computational power (Table 3). For instance, both TCT and PCA are commonly considered time consuming methods especially when it is necessary to calculate large amounts of data. The Python script code tested in this research required less than a minute to calculate all the SI and SD outputs for each case study and the process could be run from any device regardless of the local machine specifications. That is possible because Colab is a hosted Jupyter notebook service that requires no setup to use, while providing free access to computing resources. The synergy between GEE, Python and Colab is extremely effective and versatile: essentially it is only necessary to change the region of interest (ROI) in the code script to calculate the SI/SD outputs in any area of the world (Table 3). With the access to the GEE freeware planetary-scale satellite imagery dataset, our Python protocol could potentially be employed worldwide. Further, very basic coding skills are required to adapt the code to a ROI with different environmental characteristics or to customise the protocol with other SI formulas. In order to optimise the results it is only necessary to adapt the filtered image collection parameters to the peculiar environmental characteristics of the new ROI. Furthermore, the `geemap` Python module enables the interactive visualisation of the outputs directly in Colab: the images could also be stored and shared in Drive storage or downloaded to the local device for further analysis with GIS or graphical software. Finally, the modules `rasterio`, `rioxarray` and `matplotlib` enable the user to obtain downloadable plots and histograms for each output.

Nevertheless, besides the methodological advantages discussed, the current FOSS-cloud protocol still presents a few technical limitations (Table 3). First, it is necessary to keep in mind that palaeo-landscape features smaller than 10 m (the maximum S2 band resolution) are hardly recognisable. Other remote sensing techniques such as airborne/terrestrial laser scanning and ground-based geophysical survey are considerably more efficient in revealing buried features[17] but these methods entail the use of equipment that is not always available, especially in remote areas of the world. Conversely, our FOSS - cloud protocol has a planetary coverage and the resolution limit could soon be overcome with the implementation of higher resolution datasets in the GEE collections or upsampling all the S2 bands with open-source tools such as Dsen2[139]. Secondly, the protocol does not automatically assess the best multitemporal period

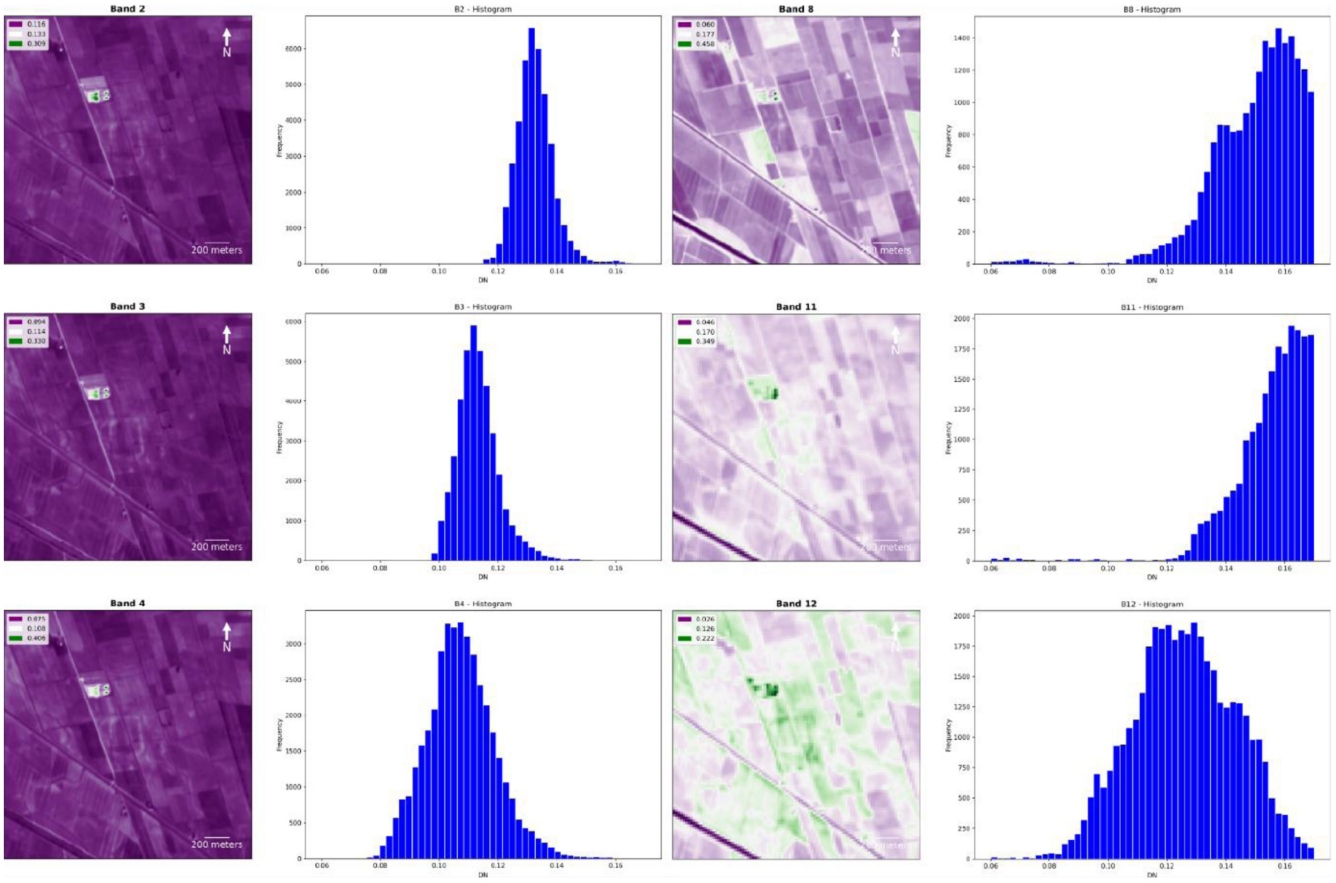


Figure 13. **Fabbrica dei Soci site, plots and histograms of the bands B2, B3, B4, B8, B11 and B12.**

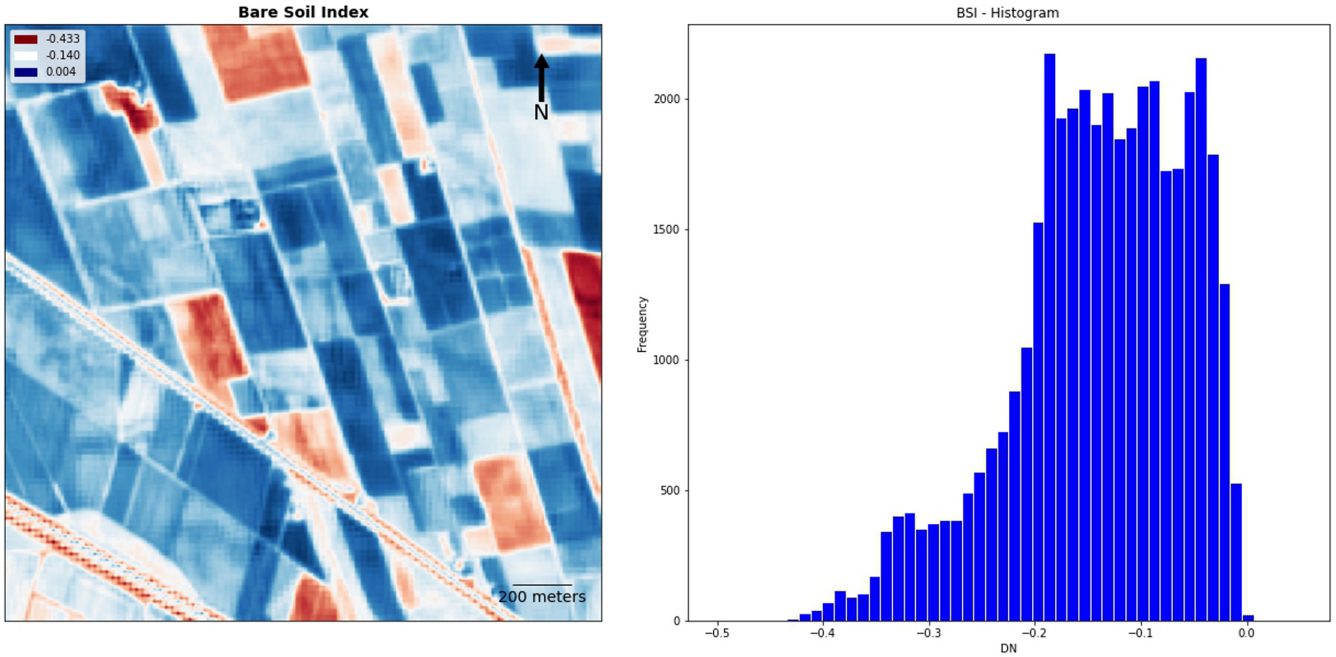


Figure 14. **Fabbrica dei Soci site, plot and histogram of the Bare Soil Index (BSI).**

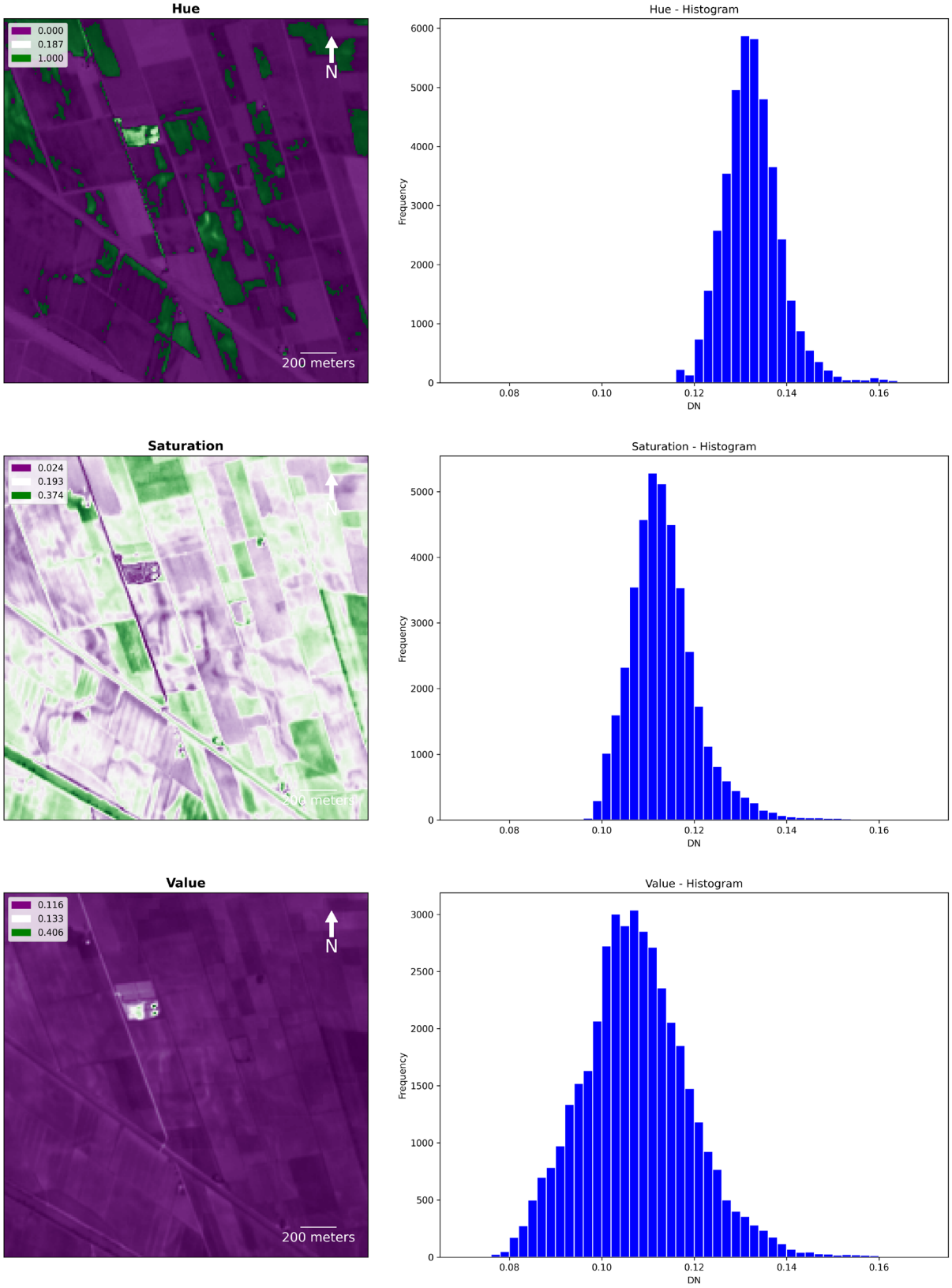


Figure 15. Fabbrica dei Soci site, Hue, Saturation and Value (HSV): plots and histograms of the bands Hue, Saturation and Value.

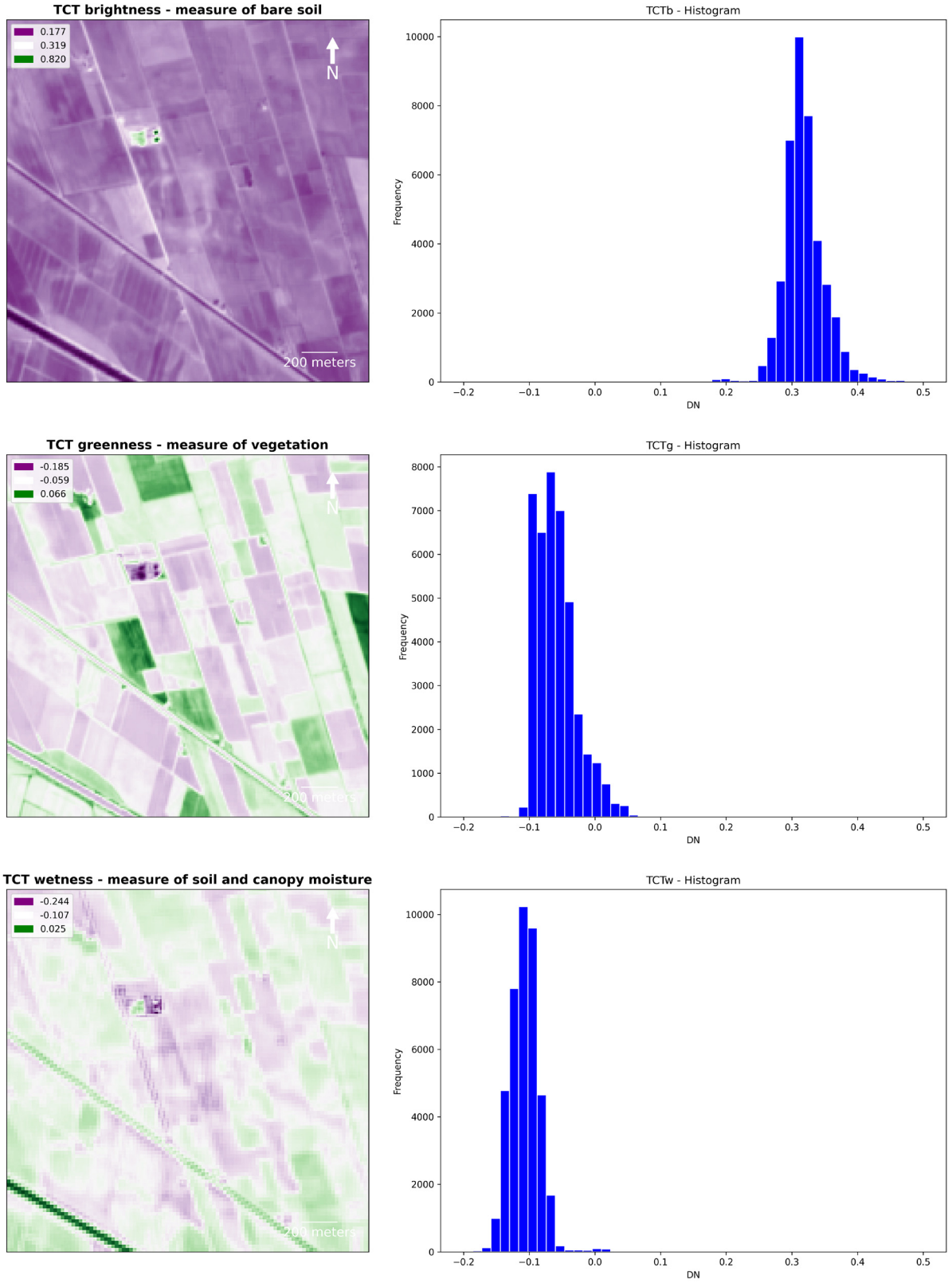


Figure 16. **Fabbrica dei Soci site, Tasselled Cap Transformation (TCT): plots and histograms of the bands Brightness, Greenness and Wetness.**

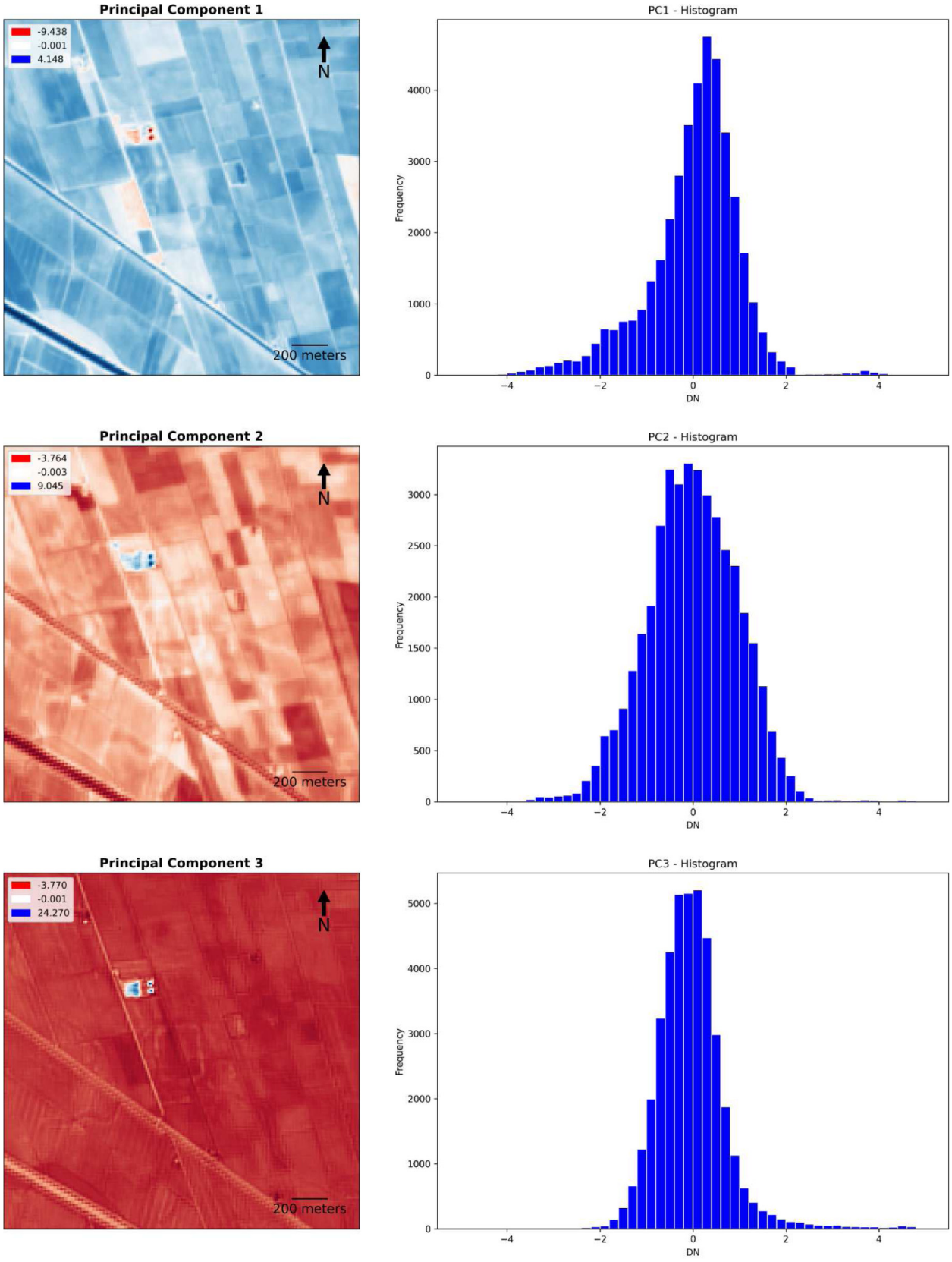


Figure 17. **Fabbrica dei Soci site, Principal Component Analysis: plots and histograms of PCA 1, 2 and 3.**

Table 3. Summary of the protocol advantages and limits discussed.

Advantages	Limits
Free and Open Access Datasets	Bands Resolution (max 10 m / pixel)
Freeware Cloud Computing	Preliminary analysis of environmental conditions of the study area is needed
Easy customisation (Basic skill coding required)	
Planetary coverage	
Interactive Spectral Signature Analysis	
Automatic extraction of frequency distribution of the digital number (DN) values of each output	

for analysis in a given area. In the test area, the choice of the timespan was based on previous scientific literature because the main research goal consisted only in verifying the potential of the FOSS-cloud protocol for the visualisation of known buried features. Nevertheless, any preliminary evaluations on a given study area will help to assess in which environmental conditions buried features are more likely to be detectable.

Conclusion

Free and open source datasets of satellite imagery and freeware cloud computing offer considerable opportunities for landscape heritage stakeholders both for identifying features and monitoring changes. In this paper, a complete cloud procedure was developed as an alternative and versatile remote sensing FOSS method for the detection of palaeo-landscape features. S2 satellite imagery has been retrieved in the GEE dataset collection and analysed through a Python script code realized in Colab. Furthermore, the same script code enables the SI and SD analysis of the image collection, previously filtered to optimize the visualisation of crop/soil marks in different case studies in the Po Plain. The outputs obtained can be visualized directly in the Colab browser or downloaded via Google Drive for further graphical applications or spatial analysis.

Choosing the right timespan for a multitemporal analysis is crucial and it depends on peculiar environmental characteristics of the ROI. In the test area of the Po Plain, the chosen period was shown to be promising for the detection of crop/soil marks. The date range was based on information from previous literature and knowledge of local environmental characteristics: the protocol performance may be different in other studies and preliminary consideration of the environmental conditions of any ROI are required.

The highest discrimination capability was observed in RGB, FSWIR and PCA outputs enabling the recording of buried riverscape features. Most of these have been checked through the available geomorphological and archaeological literature; published case studies interpreting the occurrence of buried features served as a benchmark to validate visually the script code outputs. Finally, spectral signature values show the higher performance of the SWIR bands (B11 and B12) than the other bands considered in the identification of palaeo-features: this is likely to be due to their high sensitivity to moisture content and variations over time.

To summarise, the main advantages of this method consist of: i) being FOSS, all the software used here are open-licensed; ii) working in the cloud, no powerful hardware is necessary to run the script code; iii) high adaptability, changing the ROI is possible to calculate SI and SD outputs for any area of the world; iv) very basic coding skills are required to adapt the code to a ROI with different environmental characteristics. On the other hand, the current S2 image resolution represents a limit for the identification of archaeological structures smaller than 10 m. In addition, the protocol seems particularly effective in riverscape studies while its application in different environmental conditions is still unexplored. Nevertheless, the protocol can be customised with any of the spectral index formula available enabling a wide range of potential applications. Whilst some limitations persist (Table 3), this FOSS-cloud protocol represents a potential alternative to remote sensing technologies such as lidar or geophysical survey which may be less accessible owing to technical or financial constraints. The development of FOSS-cloud procedures such as those described in this paper could support the identification, conservation and management of cultural and natural heritage anywhere around the world. In remote areas or where local heritage is threatened as a result of political instability, climate change or other factors, FOSS-cloud protocols could facilitate access to new data relating to landscape archaeology and heritage.

Data availability

Underlying data

Google Earth Engine, Sentinel-2 MSI: MultiSpectral Instrument, Level-2A

https://developers.google.com/earth-engine/datasets/catalog/COPERNICUS_S2_SR

Terms of Use

The use of Sentinel data is governed by the Copernicus Sentinel Data Terms and Conditions.

Extended data

Zenodo: *A Colab-Python script code to identify palaeo-landscape features*

https://doi.org/10.5281/zenodo.4384104[140]

This project contains the following extended data:

- GEEPY_PalaeoLandscape (Script allowing spectral indices and spectral decomposition analysis on Google Earth Engine satellite image collections).

Data are available under the terms of the Creative Commons Attribution 4.0 International Public License (CC BY 4.0).

Author contributions

Conceptualization: FB; Data Curation: FB, GDR; Formal Analysis: FB, GDR; Investigation; FB; Methodology: FB, GDR; Supervision: FB, ST; Visualization: FB, AZ; Writing – Original Draft Preparation: FB, GDR, AZ; Writing – Review & Editing: AZ, ST.

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✔ **Tobias Ullmann**
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Dear authors,

Thanks for the comprehensive revision of the manuscript. You addressed all the points I raised in my last report in a very good and reasonable manner. In my opinion, the quality of the manuscript has increased considerably and your contribution is now ready for publication.

I have very few notes on the revised version (Version 2), which I suppose can be addressed during the final production. If not, these notes will be at least documented in this report:

(1) "***Hue, saturation and value (HSV)***. *HSV (hue, saturation, value, also known as HSB or hue, saturation, brightness) is an alternative representation of the RGB colour space. In HSV [...]*" --> You used B2, B3, and B4 for the HSV transformation, I suppose? For the sake of clearness that could be mentioned here, as the HSV color space can be used for any feature combination (not only for RGB).

(2) ***"Principal component analysis (PCA)***. *The PCA transform (also known as the Karhunen-Loeve transform) consists of a linear transformation which decorrelates multivariate data by rotating the axes of the original feature space and outputs uncorrelated data120. PCA [...]*" --> Thanks for you comments and edits on this. The PCA results look most promising, in my opinion, and I welcome your discussion on the PCA and the assessments. However, here in the text it could be mentioned that the PCA was processed from all six bands (as you indicated in your answer, i.e. B2, B3, B4, B8, B11 and B12). Providing this information would avoid potential confusion, as your table 1 list all S2 bands. As well here you can mentioned how the PCA color composites (I mean the ones shown in the results, e.g. Figure 6) are composed. I suppose you used R=PC1, G=PC2, B=PC3?

(3) **Figures in the results (Fig. 6 - 11):** If available, you can add information on the used stretch in the figure caption and the band combination for the TC and PCA color composites.

Congratulations and thanks for the interesting work.
Stay well and kind regards;
Tobias Ullmann

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Geomorphology, remote sensing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 16 September 2021

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Richard Boothroyd
School of Geographical and Earth Sciences, University of Glasgow, Glasgow, UK

Thank you for comprehensively addressing the comments raised in the initial review – I have no further comments. The clarity and presentation of the revised article has been significantly improved. I hope that the FOSS-cloud method will be widely used for detecting palaeo-landscape features.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Fluvial geomorphology and remote sensing.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Version 1

Reviewer Report 21 May 2021

https://doi.org/10.21956/openreseurope.14205.r26825

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Tobias Ullmann
[1] Institute of Geography and Geology, Julius-Maximilians-Universitaet Würzburg, Würzburg, Germany
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The paper presents a python-based Google Engine approach that enables the processing of Sentinel-2 data for user-defined regions of interest. The script enables the processing of SI and SD. While the paper presents results for the detection of “anthropogenic palaeo-landscape features” in the Po plain, the script itself is not limited to be used for a specific application. The general topic of the work is of interest and the overall approach is sound and follows a clear logic. However, there are some issues that need be to addressed. There is a very positive and optimistic view on the presented approach, while at the same time it seems clear that there are some obvious limitations and drawbacks. The discussion should be extended and revisit the own results more critically.

- Introduction: It would be more stringent to present the objectives of the contribution at the end of the introduction.
- Figure 2: Provide full name of the abbreviations (BSI, HSV, etc.).
- Spectral indices, paragraph starting with *“Spectral indices that combine NIR and red channels generally…”*: Check guidelines on how to format equations. Not sure if these should stay in the text.
- Table 2: Use the band abbreviations (B1, B2…) you defined in Table 1?
- Sentinel-2 dataset; I was wondering about the cloud-masking, from my experience with the GEE and S-2 datasets there are problems to correctly mask out the clouds. Were similar findings made and is this an issue/limitation that should be reported in the discussion?
- Principal component analysis (PCA), *“Only 10-meter resolution bands were employed in PCA.”* - Why was the PCA constrained to these bands only? As mentioned above, the SWIR is of importance to highlight the crop/soil marks. So not including them might result in a loss of information?
- Figures 3 - 8: Consider placing one panel/subfigure that just shows the archaeological records. Right now, there is no chance for the reader to independently judge whether a feature is visible in the data or not. How can you be sure that the arrows indicate palaeochannels and canals? Or is this interpretation taken from the imagery? This is not clear form the figure.
- Discussion; *“this alternation of high and low rainfall intensity enabled the calculation of the mean values of multitemporal bands significant for the identification of soil marks.”* - This issue is not elaborated and not investigated. You have not checked what happens with the results when cancelling some years.
- Discussion; *“In all six case studies the best performance with respect to the SI outputs was provided by the RGB combination.” “Among the SD techniques tested in this study, the HSV*

outputs enabled the clearest identification of palaeochannels; as noted above the HSV consists of an alternative representation of the RGB colour space." - This is your expert judgement, there is no quantitative data/analysis that would support these statements.

- Discussion; *"PCA outputs returned a detailed and clear image of the riverscape palaeo-features, considering that the first two or three principal components encompass nearly 80 to 90% of the original data's variance"* I wouldn't call it a detailed and clear image, as still the identification of features relies purely on expert interpretation. Besides, as mentioned in the text the PCA was computed from the 10 m bands as such the statement on the 80-90% original data's variance is misleading as SWIR etc. were not considered?

- Discussion; As finally the expert is identifying the features, I suggest avoiding statements like *"with more accuracy", "decreasing the occurrence of false positives"* or *"significant"* as there are no quantitative analyses that would prove such findings.

- Figure 9: Colour bar/legend missing for the PCs. It is not possible to judge on the scaling from this representation. The bin size of the histograms looks to large, i.e. the true shape of the distribution is not visible. Consider redrawing the histograms and use a smaller bin size and a more fitting min/max.

- Discussion and Figure 10: *"the values of the bands that provide a better performance are those with the values more clustered, as depicted in the histograms (Figure 10)"* - It is not clear to me why the histograms should support this statement. Why should it be possible to judge on the performance in feature detection form the histograms? As the frequency of feature occurrence is much small than the frequency of the non-occurrence, some might expect the features of interest to be visible in some later PCs?

- Figure 10: Typo in *"Plots (Above) and histograms (below)"*, it is the other way round. Colour bar/legend missing.

- Discussion; How do authors see the transferability to other regions in the world, as this is mentioned in the conclusion. What problems and limitations will arise?

- Conclusion; *"methodology proposed is very effective in the reconstruction of Mid-Late Holocene landscape evolution of the Po Plain"* - this is a very strong statement that is not supported by your analysis. There is no landscape reconstruction, as well even though features can be detected by means of remote sensing, no information on the date/time etc. is available just from the imagery, but would be needed for reconstructing the landscape evolution.

Is the work original in terms of material and argument?

Yes

Does it sufficiently engage with relevant methodologies and secondary literature on the topic?

Yes

Is the work clearly and cogently presented?

Partly

Is the argument persuasive and supported by evidence?
Partly

If any, are all the source data and materials underlying the results available?
Partly

Does the research article contribute to the cultural, historical, social understanding of the field?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Geomorphology, remote sensing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 23 Aug 2021

Filippo Brandolini

We are grateful for your comments and suggestions that helped us to improve the paper considerably. In general, we tried to clarify the main aim of this paper: presenting an alternative FOSS - Cloud tool useful in detecting buried palaeolandscape features. In the first version, we did not explain clearly enough that the Po Plain served only as a test case area. Our intention was to use these well-known archaeological areas only to assess the general performance of the protocol visually. The images and the text have been improved to explain this research goal more effectively.

Following your suggestion, we added an interpretative drawing indicating all the buried features known in the literature. This improved the quality of the images significantly. Also, we clarify in the text that the cloud masking has been performed using the default S2 QA60 band provided in GEE. In relation to the PCA, we agree that considering only the 10m bands was an error: we apologise for this inadvertent problem in the code (then reported in the text!). We fixed the PCA part of the script code, and now all six bands are employed in the analysis. In the Discussion, we added more data for a general overview of the performance of each output band. Indeed, we updated the script code that now returns plots and histograms of each band automatically. Even if this does not serve as a quantitative analysis to assess the performance of detecting buried features in the Po Plain specifically, it represents a useful tool for any users to have a preliminary overview of the general performance of the outputs.

Also, the Inspector/Interactive Plot tools provided by the geemap Python module enable the spectral signature analysis to assess which bands tend to perform better in the

identification of buried features. We did not want to focus on mapping new buried features in the test case area but to show the potential and limits of FOSS and cloud resources in doing that. Consequently, we think that our main research aim is much clearer than in the first version of the paper. Finally, following your suggestion, we avoided inappropriate statements in the Discussion and Conclusion, and we added more consideration about the general pros/cons of the FOSS - cloud method proposed.

Competing Interests: No competing interests were disclosed.

Reviewer Report 28 April 2021

https://doi.org/10.21956/openreseurope.14205.r26622

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Stefano Campana
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The title does not fully match the topic of the paper. In particular it does not indicate that the automatic identification under discussion relies exclusively on the spectral signature of the images and not on other fundamental criteria usually implemented in the identification process, such as shape, size, association etc. In addition to the problem of the title, the original decision to base the identification of anomalies purely on the spectral characteristics is extremely questionable and barely acceptable as a research methodology.

The first section (*Toward a definition of "landscape heritage"*) seems to me very generic and for this reason inappropriate. I would rather suggest introducing straightforward the subject of the paper. The second section (*GIS and remote sensing in landscape studies: the satellite 'revolution'*) contains questionable statements with which many researchers/scholars in this field would profoundly disagree. In particular, perhaps, "satellite imagery has dramatically improved the quality[?] of the historic landscape characterization (HLC) approach". The authors need to explain in what sense it has done this, and in what spheres of operation? In terms of both quantity and quality of the information obtained how does it compare with what is available from other sources? For instance, in Europe but also in many other countries that have large archives of aerial photographs and/or alternative remote sensing data (such as lidar) that are accessible to specialists and the general public, and where aerial survey can be undertaken in the present day, satellite images continue to have a very limited usage in landscape studies. It is undeniable that for each site or context identified through satellite imagery vastly greater numbers have been identified (in the same areas) through aerial photography. In fact, the authors' claim is valid in only in those countries where aerial photographs and other airborne or remote-sensing datasets are not available, for instance in most of the countries in the MENA region, along with Turkey, China and Russia to name but a few.

Furthermore, in the introduction, among the reasons "why riverscapes?" the authors do not mention an absolutely crucial consideration in any form of remote sensing – that of geometric resolution. There is indeed a close relationship between the dimensions and structural characteristics of paleo-riverbeds and the spatial resolution of the satellite imagery used by the authors. However, most meaningful archaeological traces, apart from the largest enclosed settlements or ritual sites, are too small to be identified in the kind of satellite imagery that are under discussion here. Paleo-riverbeds or paleochannels are by contrast among the most widespread and easily observable features that can be recorded by this kind satellite imagery – for instance in the Po Valley in northern Italy. For the sake of clarity this should be clearly acknowledged in the text.

The reasons for focusing the research on soilmarks rather than cropmarks are unconvincing. In the section on "Material and methods" the authors state that "the detection of crop marks is affected by several issues, the most important is the phenological stage of the crops". Another influence, of course, is luck – the 'serendipity' of being in the right place to record the cropmarks when they are readily detectable – a problem which applies to any form of aerial or satellite recording which acquires imagery at a particular moment in time rather than (perhaps) at regular intervals throughout the whole course of the changing annual seasons. It is widely acknowledged that cropmark phenomena (in European landscapes) represent the most numerous source of recordable archaeological features, vastly greater than the total amount of evidence identified by any other form of remote sensing (apart, perhaps, from large-scale geophysical prospection in carefully chosen landscapes). Cropmarks provide by far the most easily identifiable archaeological traces for a very simple reason: when they are present they remain visible for a significant period of time, typically from two to six weeks in one degree of clarity or another. Moreover, throughout this time they remain visible at all times of day, from early morning to late evening. Furthermore, it is now being shown that multispectral imagery can also detect them significantly before they become visible to the naked eye (and to traditional monochrome or colour photography). Soilmarks, by contrast, are the most difficult category to identify because of their ephemeral appearance or disappearance in response to the often-transient balance between dry and wet soils under the impact of local weather conditions and the varying processes of arable cultivation. Considering the avowedly multitemporal perspective of the project, the reasons for the choice of the period appear highly questionable.

The Figures, at their present scale, are barely compressible, so small and in such low contrast that it is barely possible to see the arrows and the supposed anomalies are barely visible at all. Only in Figure 7 do there appear to be anomalies which could with reasonable certainty be associated with paleochannels.

In my view both the text and illustrations need considerable improvement before they would be worthy of indexing. A highly desirable addition would be a more realistic assessment of what can (or cannot) be achieved, in what kinds of contexts and geographical areas, by this approach to the analysis of satellite data.

Is the work original in terms of material and argument?

Partly

Does it sufficiently engage with relevant methodologies and secondary literature on the

topic?
Partly

Is the work clearly and cogently presented?
Partly

Is the argument persuasive and supported by evidence?
Partly

If any, are all the source data and materials underlying the results available?
Partly

Does the research article contribute to the cultural, historical, social understanding of the field?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Landscape archaeology and remote sensing in archaeology.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 23 Aug 2021

Filippo Brandolini

Thank you for your helpful considerations of our paper. We agree that the research goal was not clearly explained in the first version and some parts of the manuscript needed to be improved. In the introduction, we explain why we decided to focus on FOSS and Cloud tools in landscape studies, supporting our considerations with the most recent literature on the argument. In this regard, we agree with you that it is not correct to talk about a “satellite revolution” in remote sensing studies. One of the greatest improvements that have been observed in recent years is the advent of FOSS-cloud platforms that provide both open access data and freeware computational power: we reported a few of the most recent publications about the successful application of these technologies in landscape archaeological studies.

Furthermore, following your suggestion, we revised the manuscript section discussing the identification of crop/soil marks. In the first version, it was not clear that we focused on a low-vegetation period (basing that decision on previous scientific literature). Also, we mentioned only the soil marks in the first version of the paper even if some crop marks were evident in the images provided. We have rewritten the manuscript to clarify our intention. Moreover, we agree with you that soil marks are the most difficult category to identify because of their ephemeral appearance or disappearance in response to the often-transient balance between dry and wet soils under the impact of local weather conditions

and the varying processes of arable cultivation. That is absolutely true in the case of aerial images. Still, one of the main advantages of a satellite multi-temporal approach is to calculate the mean pixel value of a given period. In this case, the choice of the multi-temporal is based on previous scientific literature in which low-vegetated periods of the year seem to enable better detection of buried features in the Po Plain. In addition, we added new charts (Material and Methods) in which the GEE satellite dataset shows the date range that corresponds to low vegetated periods in the Po Plain.

Finally, we revised the Discussion and Conclusion along with illustrations to clarify that the paper's aim consists of proposing an alternative FOSS-cloud remote sensing tool rather than mapping new buried features in the Po Plain. The test case area served only to show the advantages and disadvantages of this remote sensing protocol for landscape studies. Comparing the spectral signatures of buried palaeo features and neighbouring area reveals significant differences in the SWIR bands' values. This result indirectly confirms that the multi-temporal period chosen is particularly effective in the identification of buried features since the SWIR spectral range is strongly sensitive to soil moisture content and variations over time.

Competing Interests: No competing interests were disclosed.

Reviewer Report 20 April 2021

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Richard Boothroyd
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The research article provides an interesting application of a Google Earth Engine-enabled Python approach for identifying palaeo-landscape features on the Po Plain, Italy. Using Sentinel-2 satellite imagery, the study presents a freely accessible and open-source methodology for detecting and interpreting buried features in the landscape. Several locations on the Po Plain with well-known archaeological sites are used to test the methodology, with excellent descriptions of the sites provided. In general, the methodology is clearly described and logical to follow. For each site, palaeo-landscape features (e.g., palaeochannels and canals) are detected and interpreted, with discussion of the advantages and disadvantages of the different identification approaches (including spectral indices and spectral decomposition). Overall, the study provides an important research contribution that is of interest to a range of audiences (both technical and general).

The study is original in terms of material and argument. Although established spectral indices and spectral decomposition techniques are used, the multitemporal element for detecting palaeo-

landscape features is original. The study engages with relevant methodologies and secondary literature on the topic (spanning heritage, remote sensing and fluvial geomorphology literature).

Parts of the results section could be more clearly presented. Specific suggestions are made to improve the interpretation of figures (in particular adding colour bars and re-considering the choice of symbols to delineate buried features with palaeoflow directions). Colour bars would be needed for the Figures to be scientifically sound.

On the whole, the argument is persuasive and supported by evidence. Formal accuracy assessments could be added to quantitatively assess the performance of the methodology. Sensitivity analysis could be undertaken to assess the effect of shifting the date range (i.e., from autumn-winter to spring-summer). These suggestions would strengthen some of the assertions made in the conclusions but could be deemed beyond the scope of the current 'proof of concept' work. Consideration for some of the methodological limitations could be added to the discussion – i.e., under what scenarios/environmental conditions does the methodology perform less well? This could help researchers to assess whether the methodology is suitable for their own study sites.

Source data and materials underlying the results are available – the code is accessible, well documented and easy to run using Google Colab. The source code will be a useful resource for researchers working across multiple fields and can be easily modified to apply the methodology to different regions of interest.

Specific suggestions:

- Introduction, paragraph 6 – "Archaeological investigations have confirmed that over the last 5000 years human activities have profoundly altered the spatial configuration and rate of fluvial and alluvial geomorphic processes". From a fluvial geomorphology perspective, it is unusual to see the term 'alluvial geomorphic processes' – you could replace this with 'fluvial processes' (to indicate the processes of erosion and deposition).

- Study area, paragraph 2 – "Intense rainfall (700–1200 mm per year) occurs throughout the year and the seasonal pattern of precipitation strongly influences the annual regime of the Po River" – in addition to rainfall, it would be worthwhile to mention the snowmelt component important to the annual regime (e.g., Montanari, 2012)[1].

- Materials and methods, paragraph 1 – "The mosaic of cultivated fields on the Po Plain changes all the time which makes uniform visual analysis difficult". The meaning is a little unclear here, does this refer to only the visible spectrum (i.e., RGB)? Are the same challenges experienced when using multispectral data?

- Materials and methods, paragraph 5 – "To help overcome this issue, this study adopted a multitemporal approach by calculating the mean values of bands over two ninety-day periods (January–March and October–December) of each year from 2015–2020." I was confused about the outputs here – do you produce a single image for the entire analysis period, or several annual composite images? Could you add an extra summary sentence to help the reader understand the output, e.g., 'The workflow generates a single composite image for the entire analysis period (2015-2020) containing x bands.'

- Materials and methods, paragraph 5 – "(January–March and October–December)". Was any

sensitivity testing undertaken to assess the effect of changing the date range? This could be beyond the scope of the current paper, but what effect does shifting the date range +/- 1 month or +/- 3 months have on the detection and interpretation of buried features? Sensitivity testing could provide more robust evidence to support the claims made in the conclusion.

- Materials and methods, paragraph 5 – the cloud masking procedure is not reported in the methods section but is an important step in the workflow. It would be useful to add a sentence indicating how cloud and cloud-shadow pixels were masked.

- Materials and methods, Principal component analysis (PCA) section – for TCT, you specify each band of the 6-Band Image. For completeness in the PCA section, could you specify the bands included in the 4-Band Image (R, G, B, Nir).

- Figures 3-8 – What is the rationale for not including colour bars in the figures? Adding colour bars could aid interpretation (e.g., for BSI, it is unclear whether the buried structures are indicated by locally high or locally low values). Related to this, are the values used to limit the colour maps the same between the figures (i.e., are the minimum-maximum values for BSI the same throughout Figures 3-8)?

- Figures 3-8 – Do the arrows indicating palaeochannels and canals align with the palaeoflow directions? If not, an alternative symbol (e.g., x or *) might better delineate these features so as not to imply a palaeoflow direction.

- Figure 9 – Would a colour bar be helpful here? Could more descriptive subplot titles help guide the reader (currently PC1, PC2, PC3, etc). Alternatively, could this description be included to the figure caption?

- Figure 10 – Would a colour bar be helpful here? Could more descriptive subplot titles help guide the reader (currently B2, B3, B4). Alternatively, could this description be included to the figure caption?

- Discussion, paragraph 5 – “Just like the RGB combination, whose B3 – green and B4 – red bands depict the palaeoenvironmental features with more accuracy”. Without including a formal accuracy assessment, I think it is risky to comment on the ‘accuracy’ of the feature detection (i.e., what about those features that are undetected by the methodology?). Rather than referring to accuracy, it could be helpful to discuss in terms of aiding the interpretation.

- Conclusion, paragraph 2 – “The choice of the autumn-winter period was shown to be effective for the detection of soil marks in the Po Plain. Choosing the right timespan for a multitemporal analysis is crucial”. This is an important point, but not fully supported because other time periods have not been presented/discussed (i.e., are fewer features detected if a spring-summer time period is used?). This could be rephrased to reiterate the importance of considering environmental conditions (e.g., drought) when selecting the time period.

- Conclusion, paragraph 3 – “In general, the methodology proposed is very effective in the

reconstruction of Mid-Late Holocene landscape evolution of the Po Plain." This sentence overstretches the findings of the study (reconstruction and landscape evolution infers some knowledge of the sequence of events – I don't see how the results support the statement). It could be rephrased to something more general on the utility of the tool, e.g., 'In general, the proposed methodology is a useful tool to detect and interpret palaeoenvironmental features in the fluvial landscape of the Po Plain'.

- Conclusion, paragraph 3 – "ii) working in cloud". Missing word 'the'.

References

1. Montanari A: Hydrology of the Po River: looking for changing patterns in river discharge. *Hydrology and Earth System Sciences*. 2012; **16** (10): 3739-3747 Publisher Full Text

Is the work original in terms of material and argument?

Yes

Does it sufficiently engage with relevant methodologies and secondary literature on the topic?

Yes

Is the work clearly and cogently presented?

Partly

Is the argument persuasive and supported by evidence?

Yes

If any, are all the source data and materials underlying the results available?

Yes

Does the research article contribute to the cultural, historical, social understanding of the field?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Fluvial geomorphology and remote sensing.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 23 Aug 2021

Filippo Brandolini

Thank you for your constructive criticism. Following your comments and suggestions, the

general quality of the paper was enhanced considerably. Firstly, following your suggestion, we improved the general quality of the figures. In the Discussion, we added colour bars as you suggested for each band plot and the corresponding histogram. Furthermore, we added a spectral signature analysis to assess which bands tend to highlight the palaeolandscape features better.

Regarding the symbology used to delineate buried features, we preferred to add an interpretative drawing with all the known buried features along with each site's outputs. We think that in this way, the buried features can be recognised more easily; we chose this solution because adding symbols directly to the outputs could make the visualisation difficult for readers. Moving all the symbols into a separate interpretative drawing avoids this problem. Also, we clarify in the text that the cloud masking has been performed using the S2 QA60 band.

We agree that a sensitivity analysis would be necessary to assess the effect of shifting the date range but consider this to be beyond the scope of this paper. In the first submitted version it was perhaps not explained clearly enough that the main goal was to present an alternative FOSS-cloud procedure to detect buried features. The Po Plain served only as a test case area to show the protocol's performance, so the choice of the archaeological sites and the timespan was based on scientific literature. We have tried to clarify our intentions in this respect in the revised paper. We have also added new bibliographic references in which authors indicated low - vegetation periods as better conditions to identify buried features in the test case area. Also, three new figures have been added in the Material and Methods section to support our decision to consider the low vegetation period as ideal for the test case area.

Consideration about the phenological stage of crops and field mosaicing are two common issues documented in similar published studies which we refer to in the manuscript. We have updated the script code that now returns plots and histograms of each band automatically. Even if this does not serve as a quantitative analysis to assess the performance of detecting buried features in the Po Plain specifically, it represents a useful tool for users, providing a preliminary overview of the general performance of the outputs. We did not want to focus on mapping new buried features in the test case area but to show the potential of FOSS and cloud resources to do so. In this regard, following your suggestion, we have added some considerations about methodological limitations. The two main limits are the low resolution of outputs, especially in identifying features smaller than 10 m, and the choice of the period: the latter depends on the environmental conditions of each study area, but it is something that our FOSS-cloud protocol still cannot assess automatically. To conclude, we hope that the paper's aims and conclusions are better explained and supported by the literature referenced, the images and the tables.

Competing Interests: No competing interests were disclosed.