A Google Earth Engine-enabled Python approach to improve identification of anthropogenic palaeo-landscape features

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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. Satellite remote sensing technologies have enabled significant improvements in landscape research. The advent of the cloud-based platform of Google Earth Engine (GEE) has allowed the rapid exploration and processing of satellite imagery such as the Landsat and Copernicus Sentinel datasets. In this paper, the use of Sentinel-2 satellite data in the identification of palaeo-riverscape features has been assessed in the Po Plain, selected because it is characterized by human exploitation since the Mid-Holocene. A multi-temporal approach has been adopted to investigate the potential of satellite imagery to detect buried hydrological and anthropogenic features along with spectral index and spectral decomposition analysis. This research represents one of the first applications of the GEE Python application programming interface (API) in landscape studies. 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 simply adapted and replicated in different areas of the world.

Keywords

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

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Introduction
Toward a definition of "landscape heritage"
Landslides 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\(^3\). The 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 illustrates 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.

GIS and remote sensing in landscape studies: the satellite ‘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\(^7-8\). In particular, satellite remote sensing technologies have provided significant improvements in landscape research and triggered the development of new tools in disciplines including Ecology\(^9\), Geomorphology\(^10,11\) and Archaeology\(^12,13\). For instance, in the last 20 years the use of GIS and satellite imagery has dramatically improved the quality of the historic landscape characterisation (HLC) approach\(^14\).

The advent of the cloud-based platform of Google Earth Engine (GEE) has enabled the rapid exploration and processing of more than 40 years of satellite imagery\(^15\). GEE combines a multi-petabyte catalogue of geospatial datasets and provides a library of algorithms and a powerful application programming interface (API)\(^16\). GEE eased the access to publicly available satellite imagery and earth observation tools in many branches of scientific research\(^17-20\), revealing new opportunities especially for landscape heritage applications\(^20\). 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\(^21\). Sentinel-2 carries an innovative wide swath high-resolution multispectral imager (MSI) with 13 spectral bands providing extremely useful information for a wide range of applications such as agricultural and forest monitoring\(^22-23\). 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\(^24-26\), and as a tool for scientific investigation and heritage management and preservation.

GEE can be employed in two main ways: 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”)\(^27-28\), 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\(^29\). Whilst the potential of Python in modelling landscape dynamics has been widely explored\(^30,31\), few publications have so far documented the use of the GEE Python API\(^32\). In this paper we propose a complete FOSS (free and open source software) approach to enhance palaeo-landscape feature detection through the GEE Python API in Colab.

Why riverscapes?
The potential of using the 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\(^33\). 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, often inducing profound changes to river geomorphology\(^34\). Riverine landscapes are excellent examples of landscapes which develop through complex relationships between human activities and environmental factors\(^35-37\).

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\(^38-42\).

This paper focuses on northern Italy’s Po Plain 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\(^43\). In this paper we attempt the first Python application
of Sentinel-2 data for heritage research in a Mediterranean landscape and illustrate the possibility of detecting and interpreting buried anthropogenic landscape features originating in different phases. The paper demonstrates for the first time that this kind of approach is effective in European fluvial environments.

Study area
The Po Plain (Northern Italy) results from the infilling of the depression among 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\(^44\). 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 is 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\(^45\). 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\(^46\). The highest rainfall is reached in spring and autumn while the lowest precipitation is usually registered in January and summer (June and July)\(^47\).

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\(^48\) (Figure 1). The geomorphological characteristics of the northern and southern sides of the plain differ profoundly\(^49\),\(^50\).

The area along the foothills of the Alps is characterized by the presence of Quaternary glacial amphitheatres\(^51\),\(^52\) 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\(^53\). 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\(^54\),\(^55\). 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)\(^56\),\(^57\). After that phase the Alpine tributaries of the Po River

![Figure 1. Schematic representation of the study area.](image-url)
underwent a dramatic phase of incision that caused the formation of terraces and a downstream shift in deposition zones\textsuperscript{39}. 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\textsuperscript{60,61}. The distal part of alluvial fans present 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\textsuperscript{62}. Finally, during the Late Holocene, the aggradation of river beds resulted in channel diversions and frequent inundation of flood-prone areas\textsuperscript{63}. 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\textsuperscript{64–66}.

**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 satellite imagery to enhance 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\textsuperscript{67}. 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\textsuperscript{68–70}. 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\textsuperscript{71,72}. 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\textsuperscript{73,74}. 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\textsuperscript{75}, combined with surface instability triggered by a cool climate phase\textsuperscript{76}, meant that large portions of the Po Plain changed into wetlands\textsuperscript{77}. This progressive waterlogging process endured until the beginning of the 10th century CE with significant implications for settlement and farming practices\textsuperscript{77}. Between the 10th and 14th centuries CE – corresponding to the Medieval Warm Period\textsuperscript{78} – land reclamation intensified owing to an increased demand for arable land alongside general population growth in Europe\textsuperscript{79}. 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\textsuperscript{79,80}. In the Renaissance, extensive land and water management activities advanced the process of land reclamation in many coastal and interior wetlands\textsuperscript{80,81}. 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\textsuperscript{76}. Flood defences and drainage systems were further reinforced during the 20th century to reduce the risk of inundation\textsuperscript{82}. 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\textsuperscript{73}.

**Material and methods**

The first application of GIS and remote sensing techniques to reconstruct the past landscape settings of the Po Plain dates back to the end of the nineties\textsuperscript{83}. Nowadays, 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 Plain changes all the time which makes uniform visual analysis difficult; this heterogeneity also complicates 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\textsuperscript{84,85}. 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\textsuperscript{84}.

**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).

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. The identification of crop and soil marks from aerial imagery has informed the identification of buried archaeological sites since the 1920s\textsuperscript{85–87}. 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)\textsuperscript{88,89}.

Even with the high resolution of modern satellite sensors, the detection of crop marks is affected by several issues, the most important is the phenological stage of the crops\textsuperscript{89}. 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)

To help overcome this issue, this study adopted a multi-temporal approach by calculating the mean values of bands over two ninety-day periods (January–March and October–December) of each year from 2015–2020. This choice of timespan was driven by two specific factors. The first is related to the increase in intensity and frequency of drought episodes in the Po Plain in the last decade: the longest recorded period of drought lasted from October 2016 to November 2017. As noted above, changes in soil moisture retention facilitate the detection of buried features such as river palaeochannels or ancient canals especially in severe drought periods. Secondly, autumn and winter are periods of relatively uniform land cover in the Po Plain: ploughing takes place across large areas of arable land, rice paddies have not yet been inundated and other winter crops have not yet reached their maximum growth.

The S2 satellite data were accessed through the Python module geemap in Colab, 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. Finally, 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 modules rasterio and matplotlib were used, respectively, to create individual plots for each band of the raster and histograms of their values. These representations enabled the analysis to be completed at a higher level of detail in order to identify which output bands yield better performance for the detection of features (Figure 2).

**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.

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 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. In particular, Agapiou et al. 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 (B4) spectral bands to capture soil variations according to the formula: 

\[
\frac{(\text{red}+\text{SWIR 1}) - (\text{NIR}+\text{blue})}{(\text{red}+\text{SWIR 1}) + (\text{NIR}+\text{blue})}
\]

\[
\text{BSI} = \frac{(\text{B2}+\text{B11}+\text{B8}+\text{B4}) - (\text{NIR}+\text{B12})}{(\text{B2}+\text{B11}+\text{B8}+\text{B4}) + (\text{NIR}+\text{B12})}
\]

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

<table>
<thead>
<tr>
<th>Name</th>
<th>Pixel Size</th>
<th>Wavelength</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>60 meters</td>
<td>443.9nm (S2A) / 442.3nm (S2B)</td>
<td>Aerosols</td>
</tr>
<tr>
<td>B2</td>
<td>10 metres</td>
<td>496.6nm (S2A) / 492.1nm (S2B)</td>
<td>Blue</td>
</tr>
<tr>
<td>B3</td>
<td>10 metres</td>
<td>560nm (S2A) / 559nm (S2B)</td>
<td>Green</td>
</tr>
<tr>
<td>B4</td>
<td>10 metres</td>
<td>664.5nm (S2A) / 665nm (S2B)</td>
<td>Red</td>
</tr>
<tr>
<td>B5</td>
<td>20 metres</td>
<td>703.9nm (S2A) / 703.8nm (S2B)</td>
<td>Red Edge 1</td>
</tr>
<tr>
<td>B6</td>
<td>20 metres</td>
<td>740.2nm (S2A) / 739.1nm (S2B)</td>
<td>Red Edge 2</td>
</tr>
<tr>
<td>B7</td>
<td>20 metres</td>
<td>782.5nm (S2A) / 779.7nm (S2B)</td>
<td>Red Edge 3</td>
</tr>
<tr>
<td>B8</td>
<td>10 metres</td>
<td>835.1nm (S2A) / 833nm (S2B)</td>
<td>NIR</td>
</tr>
<tr>
<td>B8A</td>
<td>20 metres</td>
<td>864.8nm (S2A) / 864nm (S2B)</td>
<td>Red Edge 4</td>
</tr>
<tr>
<td>B9</td>
<td>60 metres</td>
<td>945nm (S2A) / 943.2nm (S2B)</td>
<td>Water Vapor</td>
</tr>
<tr>
<td>B10</td>
<td>60 metres</td>
<td>1373.5nm (S2A) / 1376.9nm (S2B)</td>
<td>Cirrus</td>
</tr>
<tr>
<td>B11</td>
<td>20 metres</td>
<td>1613.7nm (S2A) / 1610.4nm (S2B)</td>
<td>SWIR 1</td>
</tr>
<tr>
<td>B12</td>
<td>20 metres</td>
<td>2202.4nm (S2A) / 2185.7nm (S2B)</td>
<td>SWIR 2</td>
</tr>
</tbody>
</table>
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 enabling the detection of moisture variations in space and time\textsuperscript{12}; recent research suggests the SWIR2 band may be valuable for calculating BSI because it seems more sensitive in terms of classification accuracy\textsuperscript{97}. 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\textsuperscript{25},\textsuperscript{41}. 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. 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\textsuperscript{12}. 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\textsuperscript{49}, 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 transformation 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\textsuperscript{12}. 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)\textsuperscript{99}. To calculate the TCT bands for S2, the WTcs recently defined by Shi and Xu\textsuperscript{100} were adopted for their better performance than previous proposed coefficient indexes\textsuperscript{101},\textsuperscript{102}. 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\textsuperscript{103}. 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\textsuperscript{12},\textsuperscript{25}. In the Python script code the PCA is calculated by diagonalizing the input band correlation matrix through Eigen-analysis (eigen()). Only 10-meter resolution bands were employed in PCA.
Results

To assess the potential of the 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 prehistory. Pre-existing information about the occurrence of buried natural and anthropogenic features provides a unique set of benchmarks to test the method. 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)\(^{104}\). 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\(^{105,106}\). The earth ramparts are easily visible in all the SI and SD analysis performed as shown in Figure 3. 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 could be interpreted as a Roman structure related to the centuration of the surrounding landscape. East of the Santa Rosa site a series of irregular palaeochannels are the result of the early Medieval waterlogging process that affected large portions of the Po Plain. An elliptical structure in the top right corner of the RGB image is likely to be a false positive: it was not detected in the other SI/SD analysis.

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\(^{34}\). 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\(^{63}\). 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 soil marks here (Figure 4). In the RGB image calculated from the S2 seasonal mean values three buried orthogonal axes are visible, remnants of the drainage system created through Roman centurisation. These palaeofeatures are slightly visible also in the FSWIR and PCA images although hardly recognisable in the others. 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\(^{63}\).

Pra’ Mantovani

The environmental context of the Pra’ Mantovani sites is similar to Valli Nuove di Guastalla. Here, recent archaeological surveys\(^{107,108}\) have registered the presence of Medieval settlements and buried Roman ditches. In all the SI/SD of Figure 5, 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 soils marks in the RGB and PCA images highlight irregular rounded features that may be interpreted as buried archaeological structures.

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 6). 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. The water management documented at this site can be considered as paradigmatic for the whole TC\(^{109,110}\). Moats, canals and palaeochannels are especially recognisable in the R, 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\(^{111,112}\). The land reclamation works unearthed several archaeological sites, in particular the Etruscan harbour of Spina\(^{113,114}\), Roman villas and the early Medieval church of Santa Maria\(^{115,116}\). 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 7) crossing the area from NW to SE. That

---

**Table 2. WTs for S2 defined by 100.**

<table>
<thead>
<tr>
<th>TCT bands</th>
<th>S2 WTs</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCTb</td>
<td>0.3510 BLUE + 0.3813 GREEN + 0.3437 RED + 0.7196 NIR + 0.2396 SWIR 1 + 0.1949 SWIR 2</td>
</tr>
<tr>
<td>TCTg</td>
<td>-0.3599 BLUE -0.3533 GREEN -0.4734 RED + 0.6633 NIR - 0.0087 SWIR1 -0.2856 SWIR2</td>
</tr>
<tr>
<td>TCTw</td>
<td>0.2578 BLUE + 0.2305 GREEN + 0.0883 RED + 0.1071 NIR -0.7611 SWIR1 -0.5308 SWIR2</td>
</tr>
</tbody>
</table>
Figure 3. Terramara Santa Rosa di Poviglio. The dot is centred on the Bronze Age settlement, the dashed lines frame buried structures and the arrows indicate palaeochannels and canals (Scale and N are indicated in the “RGB” box and are the same for all the other boxes).
Figure 4. Valli Nuove di Guastalla. The dot indicates the case study and the arrows indicate palaeochannels and canals (scale and N are indicated in the “RGB” box and are the same for all the other boxes).
Figure 5. Pra' Mantovani. The dot indicates the archaeological site, the dashed lines frame buried structures and the arrows indicate palaeochannels and canals (scale and N are indicated in the “RGB” box and are the same for all the other boxes).
Figure 6. Fabbrica dei Soci. The dot indicates the archaeological site, the dashed lines frame buried structures and the arrows indicate palaeochannels and canals (scale and N are indicated in the “RGB” box and are the same for all the other boxes).
Figure 7. Santa Maria in Pado Vetere. The dot indicates the archaeological site, the dashed lines frame buried structures and the arrows indicate palaeochannels and canals (Scale and N are indicated in the “RGB” box and are the same for all the other boxes).
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 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. In all the images, an ample crevasse splay (east sector of the area) was detected; it is likely to be the result of a severe flood event which occurred in post-medieval period. 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.

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 near-infrared (NIR) aerial photographs. Traces of buried hydrological features are visible in the area near the Roman city; Altinum was surrounded by a complex network of rivers and canals that can be recognised in all the SI/SD outputs (except in the BSI) (Figure 8).

Discussion
The results of this study show that buried natural and anthropogenic palaeo-riverscape features can be detected using a GEE Python API in Colab.

The period selected to perform the multitemporal analysis (autumn and winter) proved fruitful in terms of detection of soil marks. Buried features (both natural and archaeological) are more visible on bare soil than in cultivated fields, especially in highly mosaicised farmland, as confirmed in the cases of Valli Nuove di Guastalla and Santa Maria Pado Vetere. To identify the best period of visibility it is crucial to take into consideration crop rotation and meteorological conditions. In the Po Plain the choice was particularly strategic because the autumn and winter seasons are characterised by relatively uniform land cover. Moreover, the detection of soil marks is strongly related to the soil moisture retention of buried features. In this regard, the S2 image collection selected includes severe drought events (e.g. years 2016 and 2017) alternated with higher precipitation rate periods (e.g. year 2018); 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.

In all six case studies the best performance with respect to the SI outputs was provided by the RGB combination. Soil marks are particularly evident in the Bronze Age archaeological sites of Terramara Santa Rosa di Poviglio and Terramara Fabbrica dei Soci. FSWIR composition was particularly effective in the identification of palaeochannels and buried canals. On the other hand, the BSI index registered an overall poor performance except in the identification of positive soil marks related to the general shape of the settlement: buried structures such as moats and village perimeter are clearly detectable even in the BSI. In general, the decision to use the SWIR2 in place of SWIR1 in the FSWIR and BSI combinations returned useful results.

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. TCT and PCA were suitable for the identification of palaeo features in RGB combination. TCT was derived by the composition of TCTb, TCTg and TCTw bands and it was absolutely effective in the identification of positive soil marks. The detection of the palaeohydrography was much evident in the PCA obtained by the combination of the 1st, 2nd and 3rd principal components. As expected, PCA was the most effective method adopted in this research along with the RGB SI composition. In all the case studies, the PCA outputs returned a detailed and clear image of the palaeochannels and the palaeo-features, considering that the first two or three principal components encompass nearly 80 to 90% of the original data’s variance. Thanks to their capacity of reducing redundant information and highlighting variance for the recognition of individual elements, if we plot the four bands of the PCA separately, some principal components depict a significant contrast between the background and the palaeochannels and buried canals which, in turn, eases substantially the detection of these features (Figure 9). Just like the RGB combination, whose B3 – green and B4 – red bands depict the palaeoenvironmental features with more accuracy, the values of the bands that provide a better performance are those with the values more clustered, as depicted in the histograms (Figure 10). Nevertheless, the combination of different SI and SD approaches helped in increasing the detection of palaeo-features and decreasing the occurrence of false positives.

Furthermore, it is necessary to keep in mind that, even in outputs with the better performance as RGB and PCA, palaeo-landscape features smaller than 10 m (the maximum S2 band resolution) are hardly recognisable. This limit could soon be overcome with the implementation of higher resolution datasets in the GEE collections.

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 devices 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. In order to optimise the results is only necessary
Figure 8. Altinum. The dot indicates the archaeological site, the dashed lines frame buried structures and the arrows indicate palaeochannels and canals (Scale and N are indicated in the “RGB” box and are the same for all the other boxes).
Figure 9. Plots (Above) and histograms (below) of the PCA four bands of the Fabbrica dei Soci case study (see Figure 6).
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 in Drive storage or downloaded to the local device for further analysis with GIS or graphical software.

**Conclusion**

Free and open source datasets of satellite imagery offer considerable opportunities for landscape heritage stakeholders both for recording and monitoring activities. In this paper, a completely FOSS-cloud procedure was developed to enhance 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 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.

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 and it depends on peculiar environmental characteristics of the ROI.

The highest discrimination capability was observed in RGB and PCA outputs enabling the recording of buried hydrological 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 the script code that was developed. In other cases (e.g. Terramara Santa Rosa di Poviglio), unknown buried structures were detected in this investigation: further terrain surveys will be necessary to confirm the presence of these palaeo-landscape features. In general,
the methodology proposed is very effective in the reconstruction of Mid-Late Holocene landscape evolution of the Po Plain. The main advantages of this method consist of: i) being FOSS, all the software used here are open-licensed; ii) working in 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.

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 can facilitate the application of new scientific methods and enable the dissemination of and access to scientific information.

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: GEEPY_PalaeoLandscape

https://doi.org/10.5281/zenodo.438410

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.

Acknowledgements

The authors thank Prof. Qiusheng Wu (The University of Tennessee, Knoxville - USA) for his suggestions during the development of the script code. Part of the research has been defined with the support of the Dipartimento di Scienze della Terra “Ardito Desio” (Università degli Studi di Milano, Italy) in the framework of the project ‘Dipartimenti di Eccellenza 2018–2022’ (WP4—Risorse del Patrimonio Culturale) - Italian Ministry of Education, University, and Research (MIUR).

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Tobias Ullmann
Institute of Geography and Geology, Julius-Maximilians-Universitaet Würzburg, Würzburg, Germany

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 to be 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 from 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
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.
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.
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.
Richard Boothroyd

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

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

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.