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Sentinel-2 imagery analyses for archaeological site detection: an application to Late Bronze Age settlements in Serbian Banat, southern Carpathian Basin

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ABSTRACT

Satellite remote sensing has become a valuable tool in archaeology, allowing the monitoring of existing and discovery of new sites, and to study their surroundings. In an attempt to identify unknown Late Bronze Age (LBA) archaeological sites in the Serbian Banat region (southern Carpathian Basin), remote sensing techniques for site detection were applied using Sentinel-2 data. A multi-temporal analysis was performed, and the spectral signatures of soil marks from five known LBA settlements were analysed to determine the best conditions for the identification of archaeological features. Several principal component analyses (PCA), band combinations and vegetation indices were calculated. The vegetation indices results from soil marks at known sites demonstrated the impact of settlement characteristics (compositions, subsurface anomalies) on vegetation growth. Applying this further to identify new sites from the satellite data, one hundred and two possible archaeological locations, ranging from only a few hectares to 100 ha, were identified in Banat and Bačka, to the east and west of the Tisza River. Of the sixty-one possible sites identified in Banat, a sample was visited and their chronology confirmed, proving once again the enormous capabilities of Sentinel-2 data analyses for site detection.

1. Introduction

Satellite remote sensing data have proven to be of great value to archaeology, in remote monitoring, site detection, and landscape studies (e.g., Hadjimitsis et al., 2013; Luo et al., 2017; Masini and Soldovieri, 2017; Orengo and Petrie, 2017; Bini et al., 2018; Tapete and Cigna, 2019; Calderone et al., 2022; Pirowski et al., 2022; Agapiou et al., 2023a). As cultural heritage is increasingly affected by human impact and climate change, remote monitoring and the creation of risk assessment maps are becoming more important for conservation. These tasks are largely facilitated by access to timely information with high/medium spatial and temporal-resolution satellite imagery.

Previous constraints related to the acquisition of affordable high-resolution satellite imagery, which was inaccessible to many researchers, have been mitigated in recent years through open access to large databases of medium/high resolution global multispectral optical imagery (e.g., Sentinel-2, Landsat-8, Landsat-9). This has led to an increase in its application in several fields, including archaeology. The use of free and open-source software, and the simplification of tools and analyses, have also contributed to broadening the range of users. More recently, cloud computing has allowed the manipulation and analyses of large amounts of spatial data, circumventing issues related to hardware and software costs. This allows the analysis of hundreds, or even thousands, of satellite images and the application of mathematical functions/calculations simultaneous in a faster and easier manner, decreasing substantially the amount of time spent by the user.

Taking a step forward from the identification of sites through differences in soil characteristics (soil and crop marks) in aerial photographs, which use only the electromagnetic visible spectrum, to the broader spectrum of multispectral imagery, is not a new approach in archaeology (e.g. see review by Luo et al. 2019). In the case of Sentinel-2, this spectrum ranges from visible (VNIR) and near infra-red (NIR) to short-wave infra-red (SWIR), and in Landsat 8–9 also includes two thermal infrared bands (TIRS) (USGS EROS, n.d). When using satellite

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imagery, we are dealing with numeric data derived from variations in the reflectance proprieties of surface materials, allowing more complex analyses through the quantification of differences in surface objects, and the comparison of their specific spectral signatures.

Common applications of multispectral optical data in archaeological studies usually involve indices, band ratios, single bands or band combinations that allow for some features to be more easily recognised due to their ability to reflect or absorb radiation at specific wavelengths. More complex analytical approaches may be used, including principal component analysis (PCA) (e.g., Abate and Lasaponara, 2019; Abate et al., 2020; Brandolini et al., 2021), unsupervised (e.g., Valente et al., 2022) and supervised classifications (e.g., Alexakis et al., 2009; Agapiou et al., 2019; Orengo et al., 2020).

Inbuilding on previous research (Estanqueiro 2021a), this study aims to identify new Late Bronze Age sites in Serbian Banat, southern Carpathian Basin, through the use of Sentinel-2 data, using five known LBA enclosures as case-studies and remote sensing techniques for site detection.

2. Study area

The study area is located in the province of Vojvodina in Serbia (Fig. 1). This area is divided roughly in half by the Tisza River, separating the Banat Plains in the east from Bačka and Srem in the west. We focus on the Banat Plains on the east bank of the Tisza in this study. The Banat Plains extend beyond Serbia into western Romania and into southern Hungary.

These vast alluvial lowlands represent the southern border of the Pannonian Plain (or Great Hungarian Plain), part of the Carpathian Basin, a depressed geological unit surrounded by the Carpathian Mountains, the Alps and the Dinarides (Pavlović et al., 2017). The Carpathian Basin is filled with continental Quaternary deposits that cover thick marine and lacustrine Neogene coarse clastic deposits. The basin is represented in Serbia mainly in Vojvodina Province, which is characterised by very flat relief (100–200 m) with two low-altitude mountains areas, Fruška Gora (538 m) and the Vršac Mountains (639 m) (ibid.).

These lowlands are very prone to flooding and contain several major rivers, namely the Danube and its two tributaries, the Tisza, and the Timiş. The hydrographic network belongs to the middle Danube Basin and drains into the Black Sea (Tockner et al., 2008).

The Banat plains today are a mosaic of vast agriculture fields with the best soils in Serbia, a product of massive regulation works that took place over the last two centuries and dramatically altered the natural morphology of the river network. Once a swampy land occupied by lakes, marshes and insula (higher ground areas) where heavy flooding was frequent, the area became farmland, combining a flat relief with very fertile soils (Magina, 2015).

The most abundant and productive soil type in Vojvodina is the chernozem, which generally evolves in grassland and a humid climate (Zivkovic et al., 1972) and can be found above alluvial deposits, loess or calcareous aeolian sands.

Chernozems and semi-gleys occupy much of the territory, followed by the hydromorphic types, humogleys and fluvisols. Fluvisols can be found mainly near the large lowland rivers, while humogleys usually occur in wetlands or areas prone to temporary flooding. Solonetz and solonchak soils are also present to a lesser degree.

These halomorphic soils are spread through the region, and due to their high amount of salt are not proper for agricultural activities (Pavlović et al., 2017).

In other parts of Europe these soils have been considered degraded chernozems that have become more influenced by salts related to recent past agricultural impact/drainage and/or flooding (e.g. Shishkov and Kolev, 2014).

3. Late Bronze Age settlements

The use of aerial photography and satellite imagery has been important for discovering new Late Bronze Age settlements in Serbian Banat (Dorogostaisky and Ardelean, 2014; Dorogostaisky 2018; Molloy et al., 2020a; Darja Grosman (pers. comm.). This builds on previous macro-survey work, intensive surveys and developer led excavations which have identified LBA activity in various locales, including some settlements of the large enclosed form discussed herein (Grbić, 1951; Girić, 1994; Ćuković, 2013; Hristov, 2017; Трифуновић, 2012, 2016, 2020, Molloy et al., in press).

The emergence of these settlements around 1600/1500 BCE (Molloy et al., in press) is coincident with the abandonment of Middle Bronze

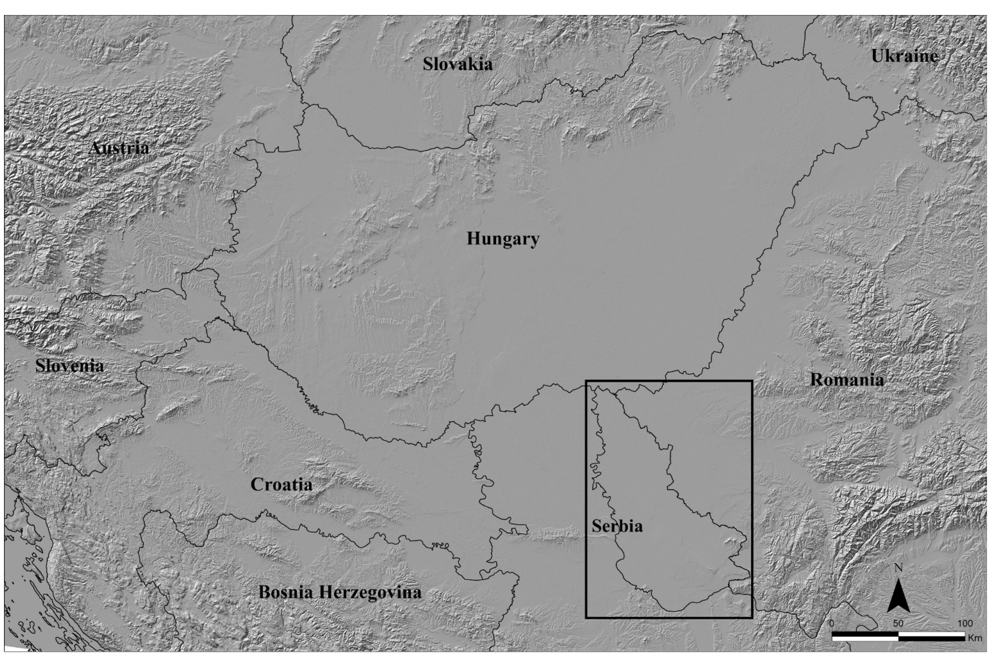

Fig. 1. Location map of study area (basemap hillshade derived from Alos DSM AW3D30 provided by JAXA- Japan Aerospace Exploration Agency). Map by M. Estanqueiro.

Age (MBA) tell sites, located close to the Danube, Tisza and Mures rivers and towards the Apuseni and Carpathian Mountains to the east (Gogâltan, 2008; O'Shea, 2013; Gogâltan et al., 2014; Ljuština, 2014; Falkenstein et al., 2016; Nicodemus and O'Shea, 2019). Contrasting with the relatively compact tells, LBA settlements are commonly enclosed (natural and/or built) and expansive. They vary in size and layout commonly being 20–40 ha in area, and up to nearly 200 ha in the case of Gradište Iđoš, the largest identified to date (Molloy et al., 2020a). The close proximity of settlements, and an overlap of possible catchment areas, has been interpreted as constituting a dense social network (ibid., Molloy et al., 2020b).

These sites to the east of the River Tisza that share many characteristics have been termed the Tisza Site Group (TSG) (Molloy et al., 2020a). This includes enclosures, defined by natural water courses and / or ditches, and clusters of subcircular pale soil marks of ca. 25 m diameter that have a high concentration of pottery sherds. These latter are thought to represent the remains of domestic structures built predominantly of soil with wattle and daub elements. The integration of clay as a building material is not rare in this region, being known from Neolithic wattle and daub houses (Sofaer 2015; Borojević et al., 2020), to more recent constructions of "nabijače", or "rammed earth homes" (Milošević et al., 2019).

A great number of the known LBA settlements were crossed by or located in close vicinity of watercourses (Molloy et al., 2020: 6). In a region prone to flooding, this suggests seasonally or throughout the year, the land surface may have been drier during the LBA. This may indicate changes occurred in the layout of the stream system and/or the climate was different to other periods of the Bronze Age and Early Iron Age (Estanqueiro, 2021b). It has also been proposed that variation in seasonal hydro-climate conditions and/or hydrology may have played a role in their abandonment in the mid-thirteenth to early twelfth centuries BC (Molloy, 2022).

An association between LBA settlements and burial mounds has been observed (Molloy et al. 2020a:7; Darja Grosman per. comm, 2019; Estanqueiro, 2020). The chronology of these tumuli is something difficult to infer without excavation, since their construction and use/reuse predates the LBA and extends to the Medieval period. Estanqueiro (2021c) has argued that the proximity of settlements to these burial mounds may be related to legitimising the presence of newcomers in that location by claiming/forging a connection to the people/ancestors that used to live there. Nevertheless, this connection is difficult to evaluate because the mounds are located on the banks of watercourses, and so the location of the settlements could be primarily related to these.

Since the pale soil marks, commonly seen in these settlements are visible in satellite imagery, we explored the capabilities of Sentinel-2 data for site detection, with the aim of identifying new sites and increasing our knowledge about LBA communities.

First, we explored the satellite data in order to determine which particular datasets best revealed soil marks, using known sites, and then we used these approaches to explore the landscape for additional potential LBA settlements.

4. Methodology

4.1. Sentinel-2 data

Copernicus Sentinel-2, with its two polar-orbiting satellites (2-A, 2-B), has a five-day temporal resolution. Multispectral data are available in thirteen bands with a spatial resolution of 10 m (bands 2, 3, 4, 8), 20 m (bands 5, 6, 7, 8a, 11, 12), and 60 m (bands 1, 9, 10) (European Space Agency, n.d; Spatial Resolution Sentinel-2, 2021). Sentinel-2 Level 2A imagery was downloaded from Copernicus Open Access Hub over a date range of November 2019 to July 2022 (Fig. 3). Level 2A imagery consists of radiometric- and atmospheric-corrected data, processed from Level 1C with Sen2Cor (Main-Knorn et al., 2017). (Other conversion methods may be used to perform the atmospheric correction, such as MAJA, 6S, FLAASH, DOS or iCOR; for a comparison between different methods see, e.g., Lantzanakis et al., 2017; Sola et al., 2018).

Level 2A data (bottom of atmosphere reflectance-BOA) was chosen because it is already atmospheric-corrected. In order to accurately measure the spectral signals of surface targets it is important to correct for the influence of absorption or scattering by atmospheric elements on the intensity and direction of the electromagnetic radiation (ER) received by the sensors at the top of atmosphere (TOA), before performing any quantitative or qualitative analyses (Bilal et al., 2019). The selection of satellite images aimed to have the minimum cloud cover over the study area, but also took into consideration visibility conditions at LBA sites examined. As most are situated on agricultural land today, the visibility of the pale soil marks is directly related to whether the fields are ploughed or not. The five LBA settlements (Molloy et al., 2020a) used as a sample – Mokrin, Melenci, Dobrica, Sakule and Pančevo – are distributed across the study area (Fig. 2).

4.2. Pre-processing

Bands 1 (coastal aerosol), 9 (water vapour) and 10 (cirrus) were not used, as the information was not relevant to the analyses. The majority of Sentinel-2 Level 2A bands are provided in 20 m spatial resolution, so it was necessary to resample them to 10 m in order to have a better pixel resolution using ArcGIS 10.7.1 software for the pre-processing steps and analyses. As the multispectral data were already orthorectified, radiometric, geometric and atmospheric corrected, no additional rectification was carried out. The individual bands from each month of the downloaded Sentinel-2 images were stacked together and the Digital Numbers (DN) converted to reflectance using the quantification value.

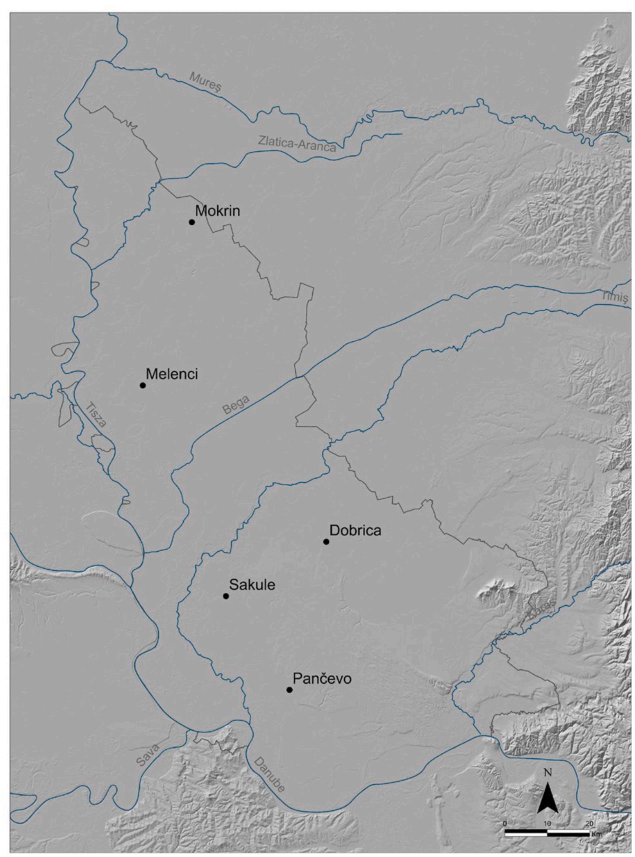

Fig. 2. LBA settlements used as sample (basemap hillshade derived from Alos DSM AW3D30 provided by JAXA-Japan Aerospace Exploration Agency). Map by M. Estanqueiro.

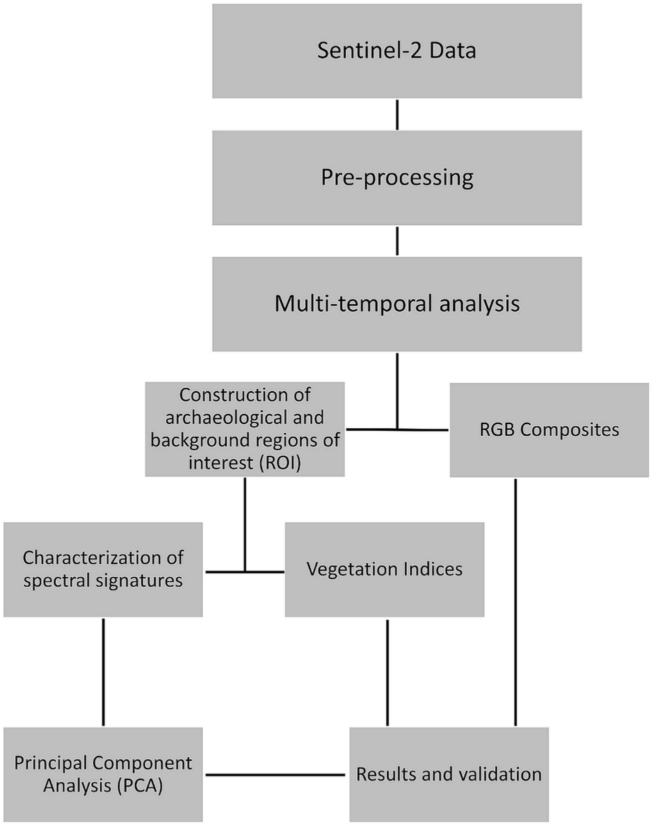

Fig. 3. Methodology flowchart.

4.3. Analyses of known LBA sites

4.3.1. Multi-temporal analysis

In order to look for differences and compare the spectral signature of the archaeological features represented by the pale soil marks and their immediate surroundings, regions of interest (ROI) were created for the five LBA sites and their vicinities. Their spectral signatures were then plotted for the twelve months of the year and compared in order to identify the months when the sites were more visible in the imagery data (see Fig. 4 for the site of Pančevo and the supplementary data for the remaining sites).

4.3.2. Spectral separability

In order to assess the spectral separability between both ROI, the M-statistic (M) was used (Kaufman and Remer, 1994). M-statistic analyses class separability using the mean (μ) and standard deviation (σ) of both samples:

$$M = \frac{|\mu_1 - \mu_2|}{\sigma_1 + \sigma_2}$$

This measure has been used to determine spectral separability between samples in several studies (e.g. Kumar et al., 2017; Moriarty et al., 2019; Luo et al., 2019; Abate et al., 2021) with values higher than 1 (M $>$ 1) translating into good separation. M-statistic was calculated for each of the ten bands analysed and the vegetation indices using the values of both ROI (archaeological sites and surroundings) gathered from the five archaeological sites during the twelve months of the year (see Fig. 5 for the site of Pančevo and the supplementary data for the remaining sites).

4.3.3. Image enhancement techniques

Several image enhancement methods (e.g., Lasaponara and Masini, 2012; Lillesand et al., 2015) were used in order to improve the visualization and detection of the archaeological features. These included a spectral enhancement through the calculation of vegetation indices, a , radiometric enhancement using a percentage linear contrast stretching of 2% on band combinations and vegetations indices, and a 2-standard deviation (σ) on PCA results. Spatial enhancement was also performed using a cubic convolution resampling on the final outputs in order to create sharper images.

4.3.4. Band combinations/RGB composites

Three band combinations were used to assess their ability to facilitate direct visualisation of the archaeological features. The combinations incorporated bands blue (B2), green (B3), red (B4), NIR (B8) and SWIR2 (B12) in the compositions 4–3-2 (natural colour), using the visible spectrum and simulating human vision; 8–4–3 (false colour infrared), commonly used in vegetation studies because chlorophyll in plants reflects near infrared light, and 12–8–4 (short-wave infrared) also commonly used in this type of study (e.g., Lemenkova, 2021).

When using band combinations to improve the detection of features we are directly interpreting satellite images, and this is somewhat subjective as the interpreter's experience has a strong impact on the assessment.

4.3.5. Vegetation indices

The following vegetation indices were calculated (see Table 1):

These indices are commonly used in archaeological studies, as vegetation growth can be affected by, and is thus an indicator for subsurface archaeological features (e.g., Lasaponara and Masini, 2007; Agapiou and Hadjimitsis, 2011).

Vegetation indices are algorithms, frequently used in remote sensing, that allow the remote quantitative and qualitative evaluation of vegetation proprieties. Studies have shown that atmospheric effects influence the radiance values in the visible and near-infrared spectra, and therefore affect the correct measurement of vegetation dynamics (see Bannari et al., 1995). Surface reflectance should be used to calculate vegetation indices, instead of digital numbers (DN), as numerical constants included in equations in several of the indices assume the use of reflectance data, such as the Soil Adjusted Vegetation Index (SAVI).

Due to the large size of some archaeological sites, and the fact that agricultural land is often divided into fields in which the vegetation is not always at the same growth stage, it was necessary to choose an individual plot of land for each known settlement analysed, and within this to select new representative regions of interest (ROI) comprising the pale soil marks and the space between these, in order to analyse their impact on vegetation growth.

4.3.6. Principal component analysis

Several PCA were performed for the months when the visibility of the sites was higher, according to the results obtained by analysis of the spectral signatures, noted above. This dimensionality-reduction technique is widely used in multispectral imagery due to interband correlation. The original data values are multiplied by eigenvectors resulting from a variance/covariance matrix. The first principal component (PC) will account for the majority of the variance in the image, and this will decrease in the subsequent PCs (PC2, PC3, PC4, etc.; Lillesand et al., 2015).

5. Results and discussion

The regions of interest (ROI) spectral signatures graphics correspond either to bare soil or vegetation. Comparing with other studies (Radoux et al., 2016; Martinez, 2017), we interpret that the vegetation signatures match the growing stages of maize, commonly cultivated in Serbia. When the fields in which the archaeological sites are located and their immediate surroundings were both ploughed, the pale soil marks indicative of the sites achieved higher values (see Fig. 4, e.g., February ROI mean spectral signature), corresponding to a greater reflectance, and showing that they have distinctive properties.

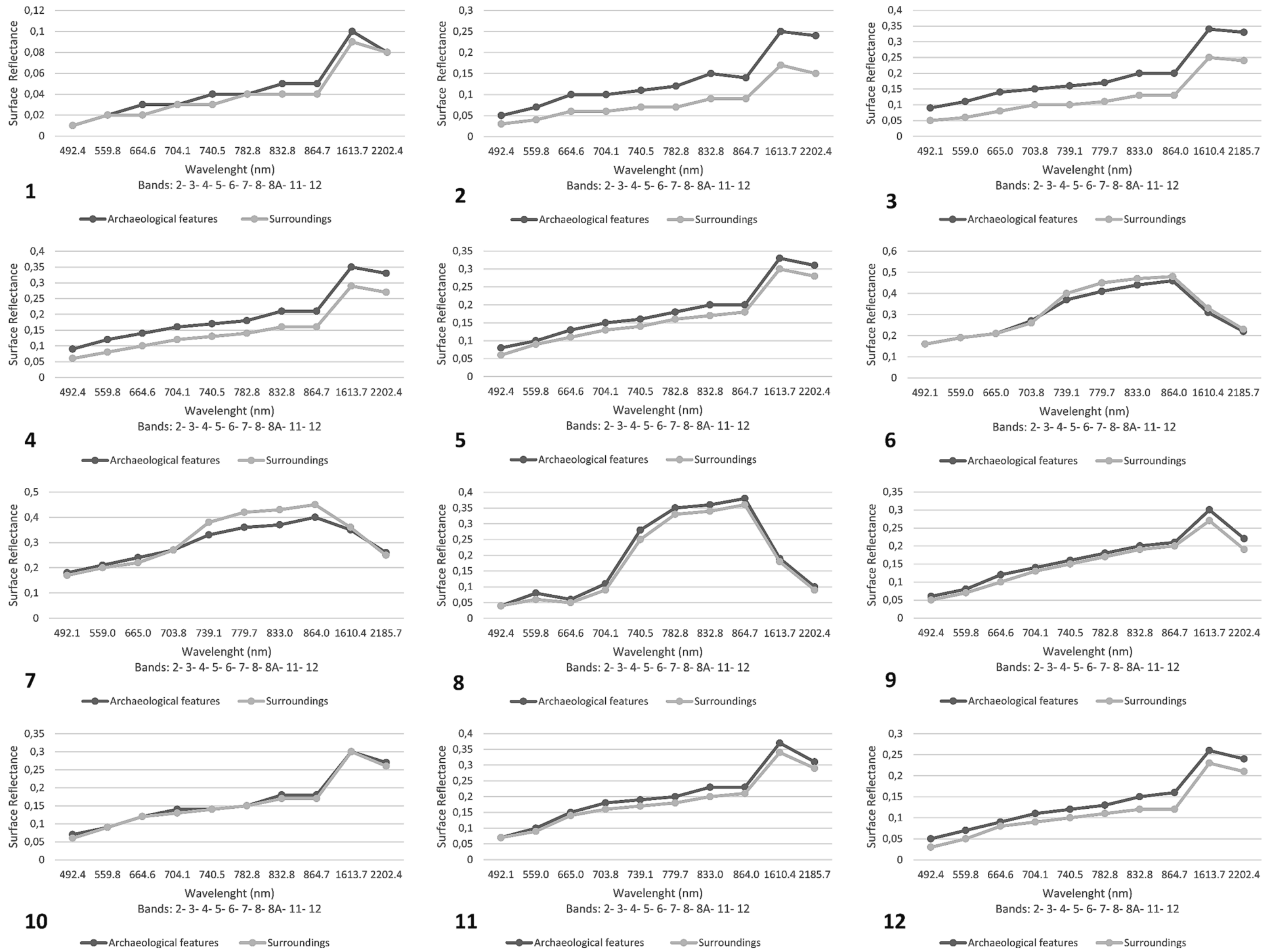

Fig. 4. Pančevo ROI mean spectral signatures for the twelve months of the year. Graphs by M. Estanqueiro.

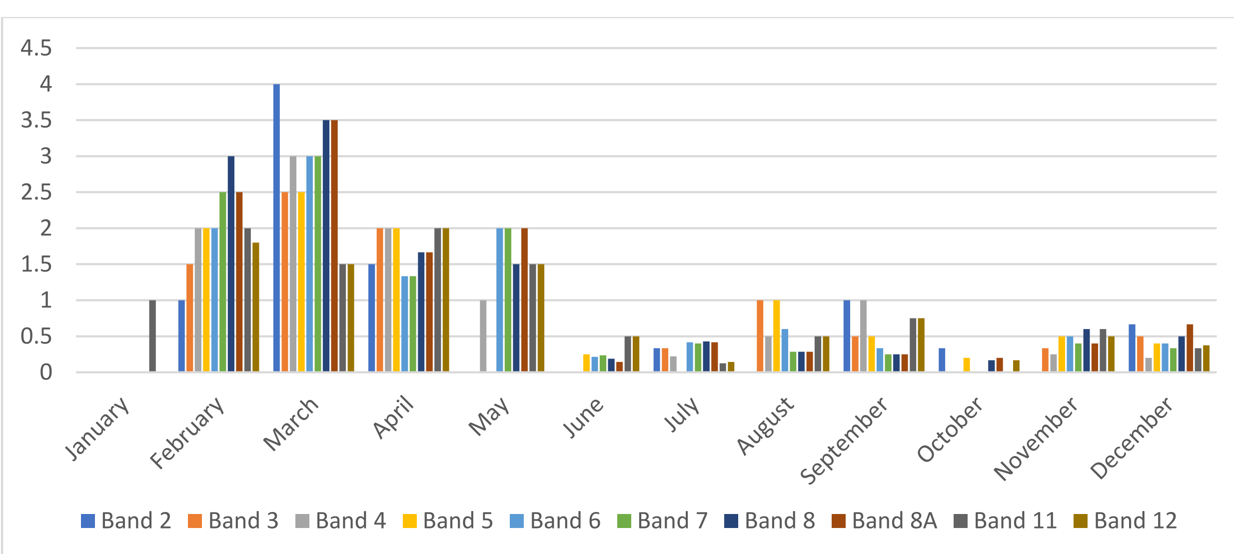

Fig. 5. Pančevo M-statistic values for the twelve months of the year and for the ten bands analysed. Graph by M. Estanqueiro.

Table 1
Calculated indices.

Index	Equation	Reference
Normalized Difference Vegetation Index (NDVI)	$NDVI = \frac{NIR - Red}{NIR + Red}$	Rouse et al., 1973
(Weighted) Difference Vegetation Index (DVI)	$DVI = NIR - Red$	Clevers, 1986
Green Difference Vegetation Index (GDVI)	$GDVI = NIR - Green$	Gitelson and Merzlyak, 1998
Green Normalised Difference Vegetation Index (GNDVI)	$GNDVI = \frac{NIR - Green}{NIR + Green}$	Gitelson and Merzlyak, 1998
Modified Simple Ratio (MSR)	$MSR = \frac{\left(\frac{NIR}{Red}\right) - 1}{\sqrt{\left(\frac{NIR}{Red}\right)} + 1}$	Chen, 1996
Tasseled Cap – Greenness (TCG)	$TCG = -0{,}28482 \times B02 - 0{,}24353 \times B03 - 0{,}54364 \times B04 + 0{,}72438 \times B08 + 0{,}084011 \times B11 - 0{,}180012 \times B12$	University of Bonn Index Database (IDB)
Soil Adjusted Vegetation Index (SAVI)	$SAVI = \frac{NIR - Red}{NIR + Red + L} \times (1 + L)$	Huete, 1988

Soil spectral reflectance differs due to varying chemical and physical soil proprieties, including texture, surface roughness, moisture, and soil composition (e.g., amount of salts, iron oxide, or organic matter) (Jensen, 2000; Streck et al., 2003). Exactly what the soil variances are in each case seen in the ROI can only be discerned through future soil analyses of samples collected in the field.

According to M-statistic results, the months in late Winter/Spring show the best separability between regions of interest, especially February and March, followed by April and May (see Fig. 5 for the site of Pančevo and the supplementary data for the remaining sites).

Regarding band combinations, all three compositions allowed the visualization of the sites, although it was easier to detect them in the 4–3–2 and 8–4–3 band composites (Fig. 6).

The vegetation indices have shown that the pale soil marks obtained lower values than the areas between them when the plots have vegetation. Although in some cases this difference is difficult to interpret directly in the resulting maps without the aid of numerical values, in other cases this is quite noticeable and easy to identify (Figs. 7 and 8).

The results obtained in the five previously known LBA settlements (Molloy et al., 2020a, Molloy et al., in press) confirmed that the pale soil marks were associated with anomalies in vegetation growth and that the indices used were very useful in clearly showing this. An inspection of other known settlements in Banat showed similar results (Fig. 9).

The M-statistic values revealed differences between the several indices, with GNDVI, NDVI and MSR achieving higher values. Although monthly values vary between sites due to local characteristics, such as different agricultural regimes or soil proprieties, August showed a good separability between ROI for most sites (see Fig. 10 for Dobrica M-statistic and the supplementary data for the remaining sites).

Four PCA were also carried out using the data from February, March, April and May as these showed good separability between regions of interest (ROI), and site visibility was higher. The PCs that allowed a better visualization of the sites was achieved by the RGB combinations using the second, third and fourth components as well as the second, third and third (Figs. 11 and 12).

All PCA were used to identify potential new sites, considering that site visibility is conditioned by the ploughing of agricultural fields, which takes place in different months. The use of PCA together with band combinations 4–3–2 and 8–4–3 allowed the identification of sixty-one potential sites distributed across the area of Serbian Banat (Table 2-supplementary data), and also of extinct watercourses. If the pale soil mark anomalies identified at the potential sites were found to be archaeological, their number would vary from a few features, possibly representing farmsteads or small settlements, to a higher concentration and wider distribution, potentially representing larger settlements.

Given that only a few sites with similar characteristics to the TSG type sites were known on the opposite bank of the Tisza, in Bačka, it was decided to explore that area further. The same methodology was applied, and forty-one possible sites were identified (see Table 2-supplementary data). Because the Serbian national database of archaeological sites is under construction and many sites are yet to be integrated into it, some of the locations found may correspond to already-confirmed sites in the Bačka area, but of which we are not yet aware.

5.1. *Evaluation of potential archaeological sites through field visits*

In order to ascertain if the locations identified as possible archaeological settlements corresponded to actual archaeological sites, and their possible chronology if so, several field visits were made to Banat in 2022 as part of the SILT survey project (Molloy et al., in press). From the sixty-one sites identified in the region of Serbian Banat, twenty-four were visited and surface archaeological material was collected from these locations. Twenty-two corresponded to archaeological sites, with only two not presenting any cultural material in the plough. Two additional locations out of the sixty-one potential sites were later confirmed as sites, one based on old records (Dragan Jovanović, pers. comm.) and the second through information from Darja Grosman (pers. comm.) and visited by the SILT project.

In total, from these twenty-six locations, twenty-two had archaeological surface material, two were tumuli and the remaining two did not have surface artefact scatters. The twenty-four locales identified from the satellite data and confirmed as archaeological sites (Fig. 13) represent 39% of the sixty-one possible locations in Banat.

Ceramic finds collected and dated to the LBA by the SILT survey team were recovered from eighteen out of the twenty-two sites (81.82%). Medieval pottery sherds were present in 40.91%, and 31.82% had Sarmatian surface materials (Molloy et al., in press).

Neolithic scattered artefacts were found in four sites (18.18%) and in

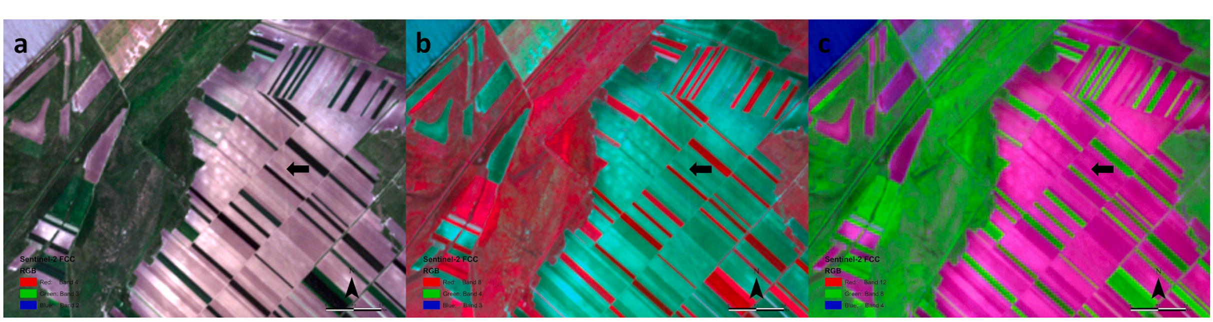

Fig. 6. Dobrica Sentinel-2 band combinations (6a. Sentinel-2 FCC 4–3–2, 6b. Sentinel-2 FCC 8–4–3, 6c. Sentinel-2 FCC 12–8–4). Images by M. Estanqueiro.

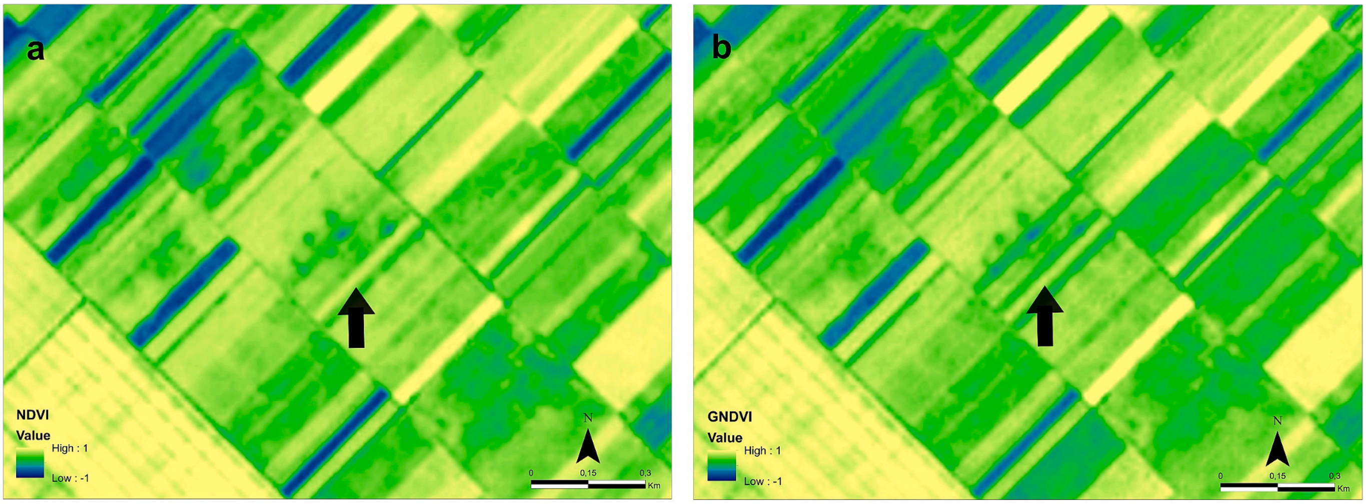

Fig. 7. Sakule NDVI and GNDVI resulting maps for August (7a. NDVI, 7b. GNDVI). Images by M. Estanqueiro.

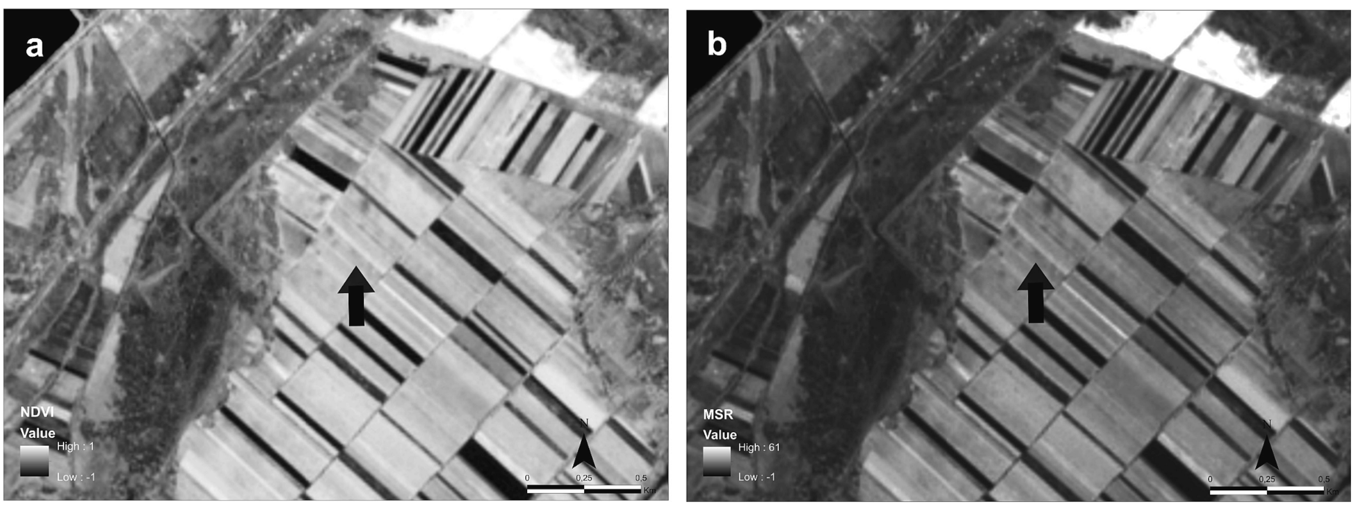

Fig. 8. Dobrica NDVI and MSR resulting greyscale maps for August (8a. NDVI, 8b. MSR). Images by M. Estanqueiro.

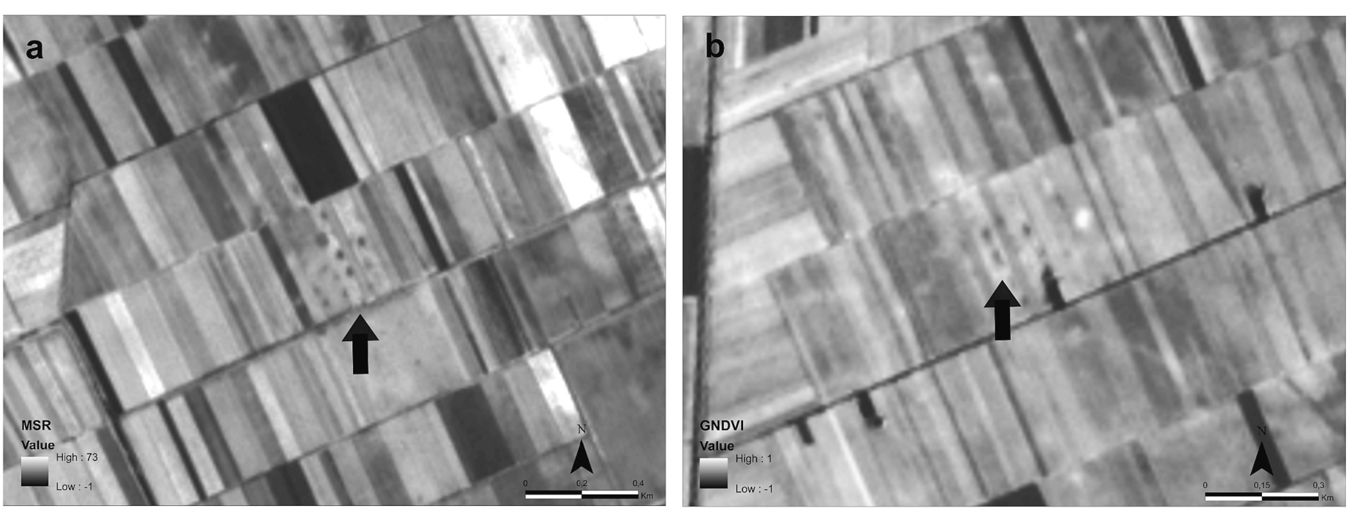

Fig. 9. Crepaja MSR and Debeljaca GNDVI resulting greyscale maps for August (9a. Crepaja, 9b. Debeljaca) Images by M. Estanqueiro.

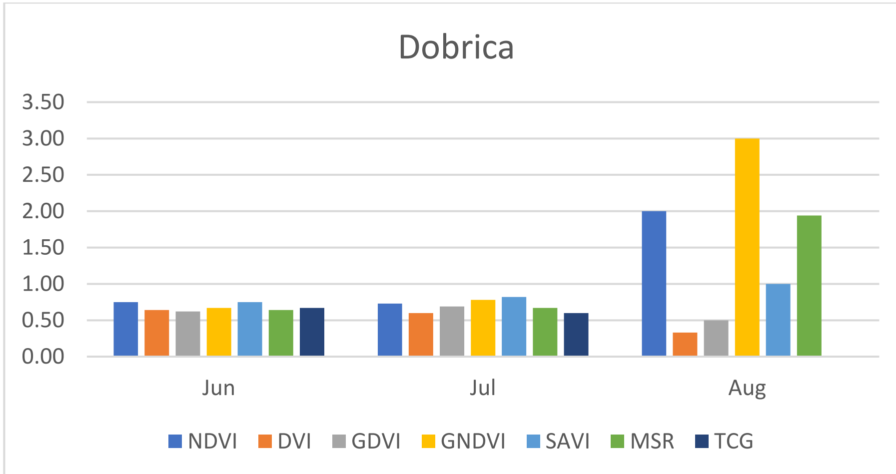

Fig. 10. Dobrica vegetation indices M-statistic values. Graph by M. Estanqueiro.

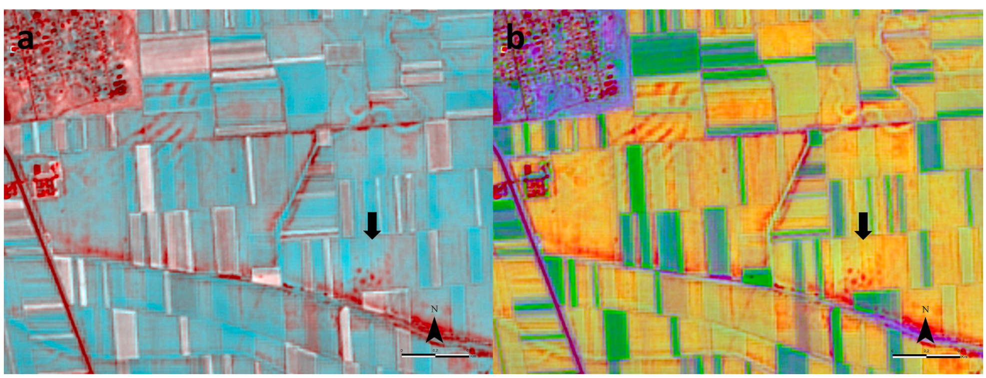

Fig. 11. Melenci February PCA RGB composite (11a. PCA output using the 2nd, 3rd and 3rd components, 11b. PCA output using the 2nd, 3rd and 4th components). Images by M. Estanqueiro.

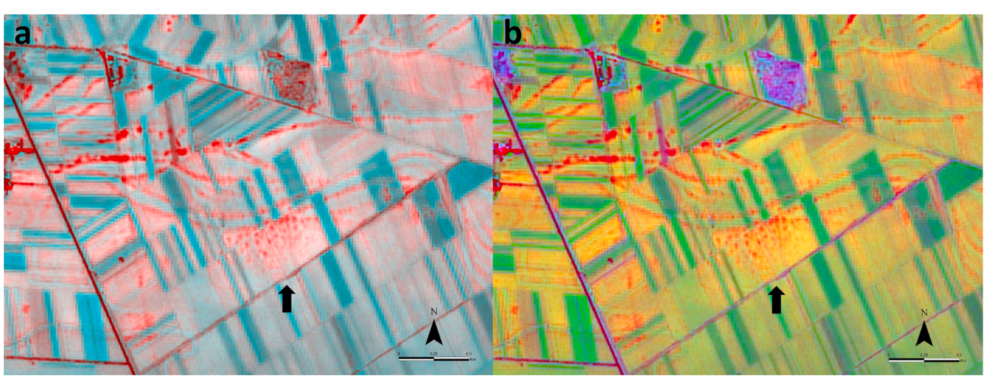

Fig. 12. Mokrin February PCA RGB composite (12a. PCA output using the 2nd, 3rd and 3rd components, 12b. PCA output using the 2nd, 3rd and 4th components). Images by M. Estanqueiro.

three (13.64%) Iron Age pottery sherds. One location covered a large area with several pale soil marks, with one of these corresponding to a new Middle Bronze Age tell site (Barice Bugarska Humka). In its vicinity material from the early phase of the LBA was also recovered (see Table 2 in supplementary data).

Two locations were tumuli and the surrounding pale soil marks are currently considered to be of unknown origin. The use of similar earthen materials on structures in the past, could be responsible for the pale soil marks visible in sites with chronologies other than LBA.

The reason for a lack of artefact scatters in two locations with characteristic soil marks is unknown, but many factors, including local depths of both soil and ploughing, can be involved in how surface collections of artefacts relate to the presence or absence of subsoil features (e.g. Odell and Cowan 1987: Boismeier 1997; Trachet et al. 2017). Artefact scatters are well known to migrate over time with ploughing and other land-use histories and impacts (Lewarch and O'Brien 1981; Wildesen 1982).

Assumed 'natural' pale soil marks are very common in the study area and could also be related to micro-topographical or micro-hydrological variations affecting plant growth, leaving to the researcher the task of

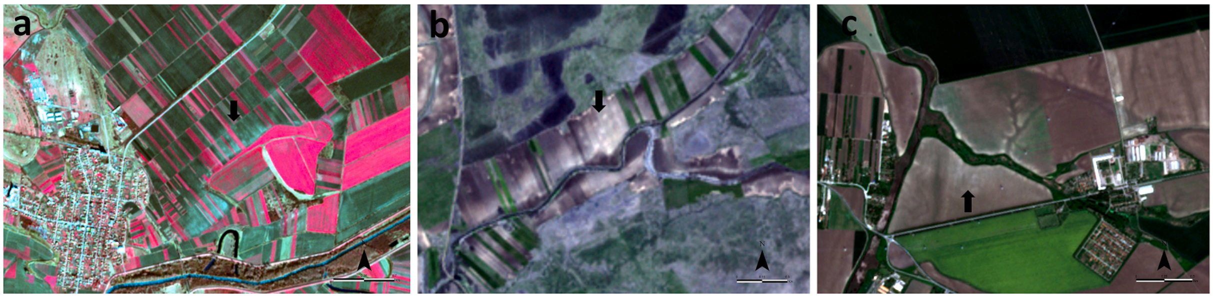

Fig. 13. Examples of confirmed LBA sites (13a. Sečanj 6 -C.E, 13b. Zrenjanin 3- R.E, 13c. Pančevo 5- I.F). Images by M. Estanqueiro.

differentiating them. To potentially eliminate 'natural' soil marks from the list of potential archaeological sites we can look at their surface morphologies, and this is how we targeted our list of possible archaeological sites.

Nevertheless, the approach using targeted datasets and vegetation indices has been extremely successful in locating sites of great interest for ground-truthing and excavation.

Regarding the reasons for the sites showing up as pale soil marks in particular (vs. dark, organic soil marks, which are also very common), authors Dragan Jovanović and Marta Estanqueiro have suggested either that the material used to build LBA dwellings included loess recovered from ditch or pit digging, and this loess inclusion is responsible for the soil colouration (D.J), or that the 'lighter' sediments correspond to the remains of some type of plaster, probably made using lime or calcite, mixed with other materials that could have included ashes, loess, etc. (M.E). The use of loess as a building material has also been argued previously by Molloy et al. (2017). A further possible process involved is differential leaching/micro-hydrology, which could relate to all of the above and reflect variations in texture and chemistry between the anomalies and the surrounding soil (suggested by co-author Helen Lewis). All such suggestions can only be addressed through further research in the field and from soil samples.

6. Conclusions

The Sentinel-2 data have proven to be of great value for the identification of archaeological features in Banat, with their medium spatial resolution, revisit period and global coverage, allowing free access to a large library of multispectral imagery and making data available that is already atmospheric corrected. Taking into account the large extent of the study region and the average diameter of the archaeological pale soil marks (ca. 25 m), Sentinel-2 imagery was the best choice from the freely available satellite multispectral data, with its 10 m spatial resolution. The use of high-resolution multispectral imagery could improve the results obtained by allowing the detection of smaller features, but this option involves currently costs to the user.

Considering the results achieved in this study, where sixty-one potential archaeological site locations were identified in Banat and forty-one in Bačka, with a percentage of 39% already confirmed in the first area, we believe the outcome to be very promising. Follow-up in the field confirmed that out of the twenty-two sites with archaeological material 81.82% had LBA surface diagnostic artefacts. From these, one is a new Middle Bronze Age tell site, designated Barice Bugarska Humka with Middle and very early Late Bronze Age material found in the surrounding area. Additionally, 40.91% had Medieval surface material and 31.82% Sarmatian. Four sites (18.18%) had Neolithic scattered artifacts and three (13.64%) had Iron Age pottery sherds (see Table 2 in supplementary data).

The eighteen sites identified by Estanqueiro and confirmed to be LBA by Molloy and Jovanović were integrated in the SILT project database (Molloy et al., in press), although with different designations to facilitate the integration into the pre-existent database.

By using multi-temporal analysis and studying the spectral signatures of archaeological soil marks over twelve months, it became possible to distinguish the better months for site visualization, as well as to improve site identification by performing PCA and band combinations.

Vegetation indices have shown that the pale soil marks characteristic of known LBA sites also impact vegetation growth, and are an indicator of archaeological surface scatters, and likely of sub-surface archaeological features. The use of these indices has already proven very useful in detecting archaeological features in previous studies. Recently, in the neighbouring countries of Romania and Hungary these were applied to large LBA fortifications that share some common characteristics as the LBA sites in our study area, including the presence of ditches and/or ramparts, resulting in the identification of several unknown features (Agapiou et al., 2023a; Agapiou et al., 2023b). In general, we found that these indices should be used with caution when applied to areas where fields are divided into small plots, and where seeding and ploughing are carried out at different times, as these variations contribute to misinterpretations when comparing plots with vegetation in different growth stages. To avoid this problem, the regions of interest (ROI) representing the soil marks and their surroundings should be examined in the same plot, where the vegetation will be at the same growth stage.

The use of satellite data can be very useful not only for site detection, but also to actively monitor natural and cultural heritage remotely, and therefor greatly contribute to its protection from human pressure and natural phenomena.

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CRediT authorship contribution statement

Marta Estanqueiro: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Funding acquisition. **Aleksandar Šalamon:** Investigation. **Helen Lewis:** Investigation, Writing – review & editing. **Barry Molloy:** Investigation, Writing – review & editing, Funding acquisition. **Dragan Jovanović:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2023.104188.

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