Linear Spectral Unmixing for the Detection of Neolithic Settlements in the Thessalian Plain, central Greece

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Abstract. Vegetation crop marks may be formed in areas where vegetation overlays near-surface archaeological remains. These features retain soil moisture with different percentage of moisture compared to the rest of the crops of an area. Depending on the type of feature, crop vigour may be enhanced or reduced by buried archaeological features. Satellite imagery has been already applied successfully in several archaeological investigations for the detection of buried archaeological features based on such crop marks. However, such features can only be classified when their spectral characteristics are different from their surroundings. Difficulties might occur when spatial resolution (pixel size) of the satellite sensor is low enough in order to distinguish crop marks from their surroundings. In these cases up-scaling techniques, like linear spectral un-mixing (LSU), can be used in order to improve spatial resolution and to enhance image results. The aim of this paper is to assess LSU technique for the detection of archaeological sites. LSU is based on the assumption that within a given scene, the surface is dominated by a small number of distinct materials that have relatively constant spectral properties (called endmember). LSU technique was evaluated at several Neolithic tells (magoules) located at the Thessalian plain. Different multispectral satellite images (mainly Landsat TM/ETM+) have been used for this purpose. The final results were compared with other standard remote sensing techniques like Principal Component Analysis, vegetation indices, Tasseled Cap and ground spectroradiometric data.

Keywords. Linear spectral unmixing, detection of buried archaeological remains, Neolithic settlements, spectral signature, vegetation indices, Tasseled Cap algorithm.

1. Introduction

Remote Sensing techniques offer new perspectives in archaeological research [1], [2], [3]. The application of such non destructive practices has exhibited great prospective for archaeological investigations in the past years. Remote sensing includes a variety of methods such as ground geophysical surveys using either penetrating radars or magnetometers [4] or aerial and satellite imagery [5], [6]. Indeed multispectral and hyperspectral satellite images may be used for the detection of buried archaeological features when changes of the spectral signature of vegetation is occurred due to the presence of these buried remains.

Lasaponara and Masini [7] emphasised that subsurface monuments can be successfully recognized using high multispectral resolution satellite images. These subsurface features were detected as spectral signature anomalies. The use of hyperspectral satellite data has been also discussed in different studies in order to identify architectural remains as crop marks [8], [9].

In detail, archaeological crop marks may be recognized by the enhancement of the satellite images. This can be performed by exploiting several techniques including vegetation indices (VIs) or other algorithms such as the Tasseled Cap. Such techniques are widely used in order to monitor the seasonal or even long-term variations of structural, phenological and biophysical parameters of land surface vegetation covers, for several applications of remote sensing. Indices are quantitative measures, based on vegetation spectral properties that attempt to measure biomass or vegetative vigor. Theoretical analyses and field studies have shown that VIs are near-linearly related to photosynthetically active radiation absorbed by plant canopy, and therefore to light-dependent physiological processes, such as photosynthesis, occurring in the upper canopy [10], [11].

Recently, ground spectroradiometers have also been proposed for archaeological investigations as an alternative technique for supporting archaeological field work. As it was found, based on several ground hyperspectral measurements, ground spectroradiometers may be used for archaeological investigation from different perspectives: pre-processing for the satellite images (e.g. atmospheric correction), confirmation of satellite results or even for predictive modelling [12], [13], [14].

However, difficulties might occur when spatial resolution (pixel size) of the satellite sensor is low enough in order to distinguish crop marks from their surroundings. In this case, “pure” elements are “mixed” in the satellite image and therefore a “mixed” pixel (mi-xel) is occurred (Figures 1, 2).

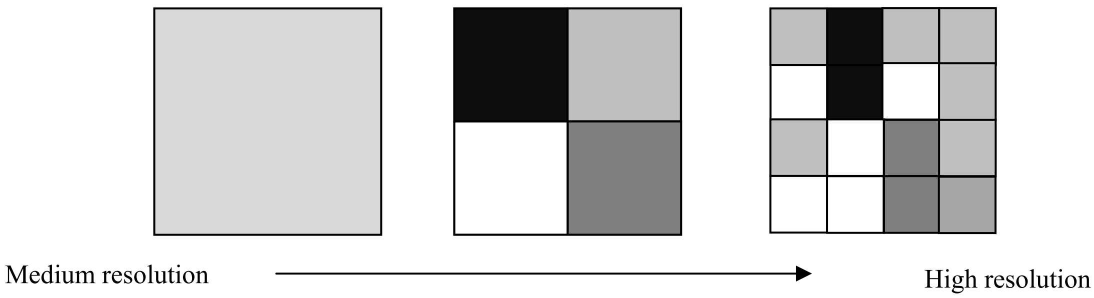

Figure 1: Example of a mixed pixel in different resolutions.

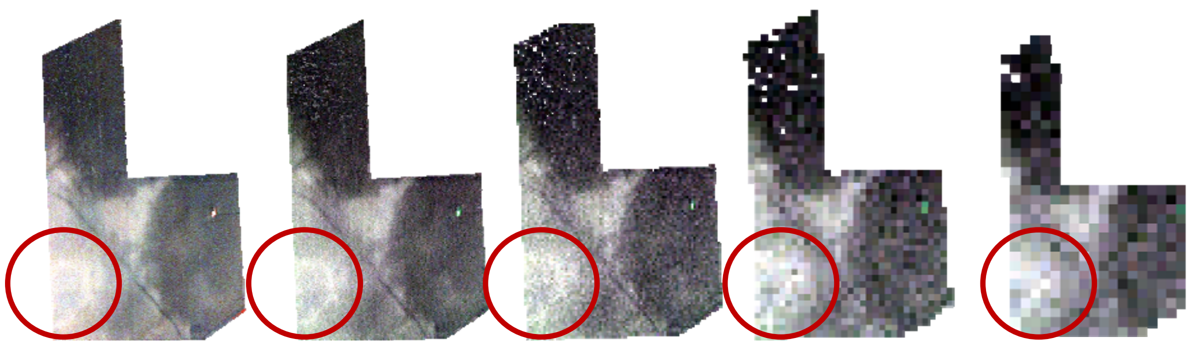

Figure 2: Crop mark (Nikaia 16 site at the Thessalian plain) in circle in different scale resolution (1m, 2m, 4m, 10m, 15m and 30m pixel resolution from left to right).

Mixed pixel phenomenon can be problematic for several applications and not only for archaeological research. Classification techniques, which are widely used for the taxonomy of a multispectral/hyperspectral image to thematic classes, is a characteristic example of this phenomenon: mixed pixels, due to their spectral signature, are classified in the wrong class. In order to overcome this limitation of the satellite raster datasets, scale-down techniques are used. Scale-down techniques (top-down approach) aim to decomposed information at a certain geographical scale into its constituents at smaller scales. Therefore these scaling techniques, like spectral un-mixing (LSU), can be used in order to improve spatial resolution and to enhance the final image results.

In detail, spectral unmixing is the procedure by which the measured spectrum of a mixed pixel is decomposed into a collection of constituent spectra, or endmember, and a set of corresponding fractions, or abundances, that indicate the proportion of each endmember present in the pixel [15].

The constrained linear spectral mixing (LSU) model was applied in this study. In this model, the sum of the abundance should be equal to 1 as shown in Equation 1. The mathematical equations of the model and its constraints are given by:

$$\mathbf{x} = S\mathbf{a} + \mathbf{r} = \sum_{i=1}^{m} a_i \mathbf{s}^i + \mathbf{r}; \qquad \text{[Eq. 1]}$$

$$\sum_{i=1}^{m} a_i = 1 \text{ and } a_i \geqslant 0 \ \forall i,$$

where **x** the measured spectrum of an image pixel**, S** is an n x m matrix whose columns are the **m** endmember spectra assumed to be independent, the entries of **a** are the corresponding abundances or fractions of the endmember spectra present in **x**, and **r** represents a noise vector. Figure 3 presents the methodological diagram of the LSU application for satellite images. The initial satellite image is considered as a mixed image. Using either ground spectroradiometric measurements or spectral signatures from the image, the user selects the endmember spectra. Special attention should be given since these spectra should be characteristic for the area of interest. Furthermore these spectra are considered as "pure" spectra. Then the LSU algorithm is applied. The final result is the abundance information.

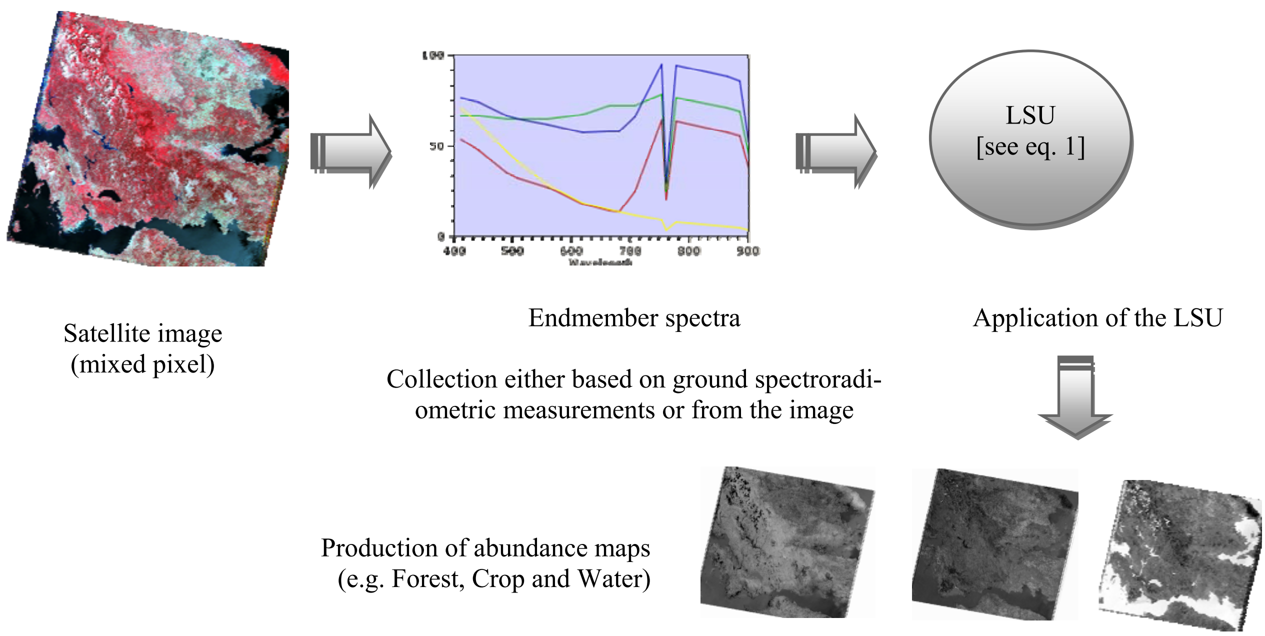

Figure 3: Methodological diagram for the application of the LSU algorithm.

This paper is organised as follows: Chapter 2 presents the LSU results from the Palaepaphos archaeological site located in the SW part of Cyprus. The results have been confirmed with ground geophysical surveys and spectroradiometric measurements. After the promising results found at the Palaepaphos site, the potential use of LSU was evaluated for the Neolithic tells situated at the

Thessalian plain. Chapter 3 presents the prehistoric background of these tells along with other ground measurements performed by the authors. The Chapter is then focused on the post-processing of Landsat satellite images including LSU, vegetation indices and Tasseled Cap algorithm. The paper ends with some preliminary conclusions.

LSU algorithm was applied both in a Matlab environment, specially designed for the aims of this study, and the Beam Visat 4.9 software.

2. Palaepaphos archaeological site, SW Cyprus

2.1. Historical background

Palaepaphos site is located on the SW coast of Cyprus (Figure 4) and is an extensive yet insufficiently defined archaeological landscape. Palaepaphos is considered a significant archaeological site since it contains many important monuments related to the Bronze Age history of Cyprus. Its few visible secular and sepulchral monuments and its famous open-air sanctuary to an aniconic deity, who was to become known as Aphrodite, are scattered over an area of two square kilometers [16].

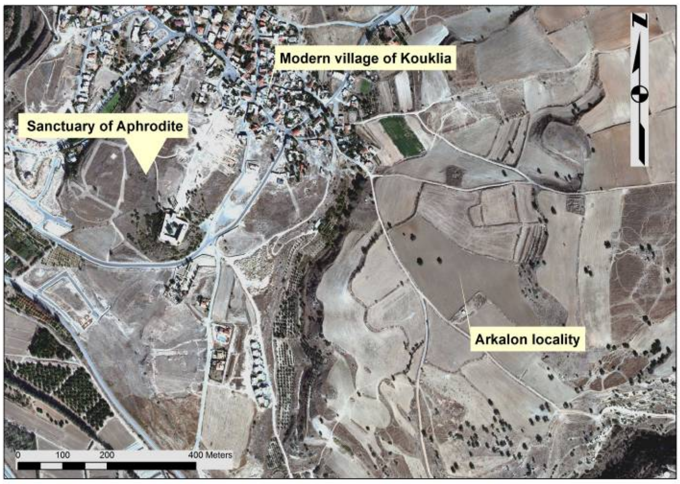

Figure 4: Palaepaphos archaeological site is located a few kilometer east of Paphos town, SW Cyprus.

2.2. Previous results

In the last few years systematic archaeological investigations were carried in Palaepaphos area, following the results of geophysical surveys that were carried out in different sections of the site [17], [18]. The results after the geophysical surveys identified areas of interest which contain potential subsurface monuments. One of such areas is in the locality of Arkalon in Kouklia, just east of the village (Figure 4). The results showed the presence of architectural remains, identified as a large rectangular structure with high magnetization. Linear features appear to be aligned in N-S and W-E directions delineating a rectangular structure that extends for more than 70 m (Figure 5).

Figure 5: Magnetic anomalies near Arkalon, Kouklia [19].

In addition, ground spectroradiometric measurements taken at the Arkalon locality were able to confirm the geophysical results (Figure 6) [13], [14]. GER spectroradiometer was used. This instrument can record electromagnetic radiation between 350 nm up to 1050 nm. It includes 512 different channels and each channel covers a range of about 1.5 nm. The field of view (FOV) of the instrument is 4^{o}. Several campaigns were organised in order to evaluate the potential use of ground spectroscopy for archaeological purposes during the phenological cycle of the barley crop cultivated in the Arkalon locality.

Figure 6: Ground spectroradiometric campaigns using the GER 1500 at the Arkalon locality, Palaepaphos archaeological site.

Spectral signatures were taken along several transects over the geophysical anomalies. In this campaign four transects, as shown in Figure 7, were carried out. The sections A - C were applied in the southern anomaly from west to east and the section D was performed in the N-S anomaly. The spectral signatures of the sections (A-D) results are shown in Figure 8. The measurement which corresponds to the subsurface anomaly is indicated with an arrow in the diagrams.

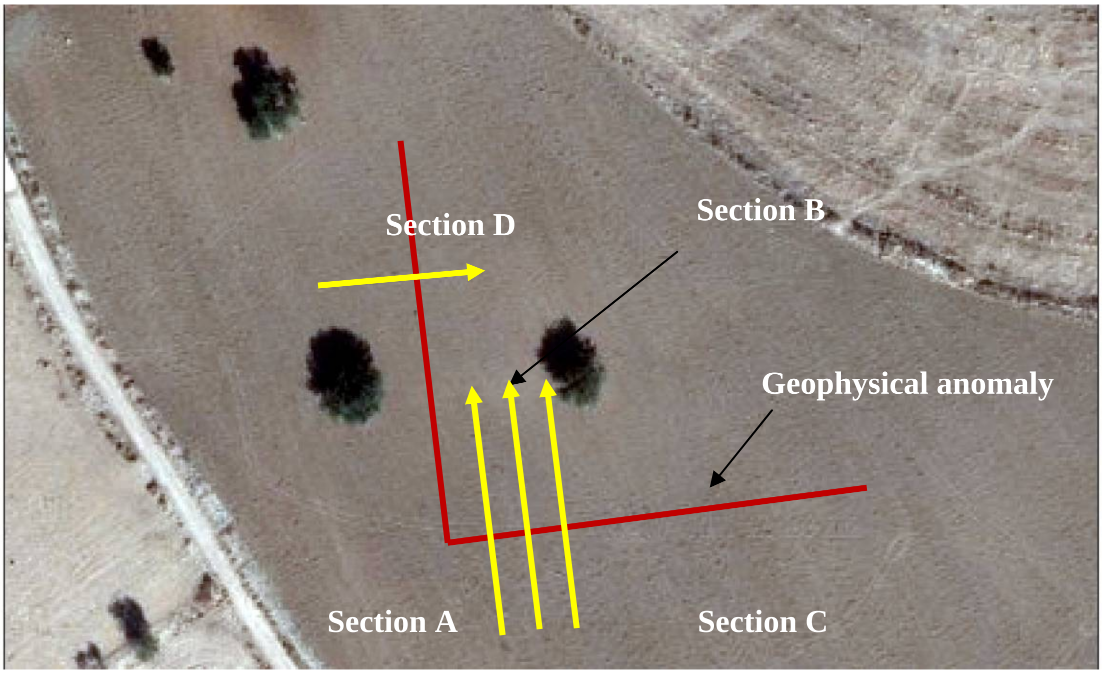

Figure 7: Ground spectroradiometric section over a main geophysical anomaly in the Arkalon locality.

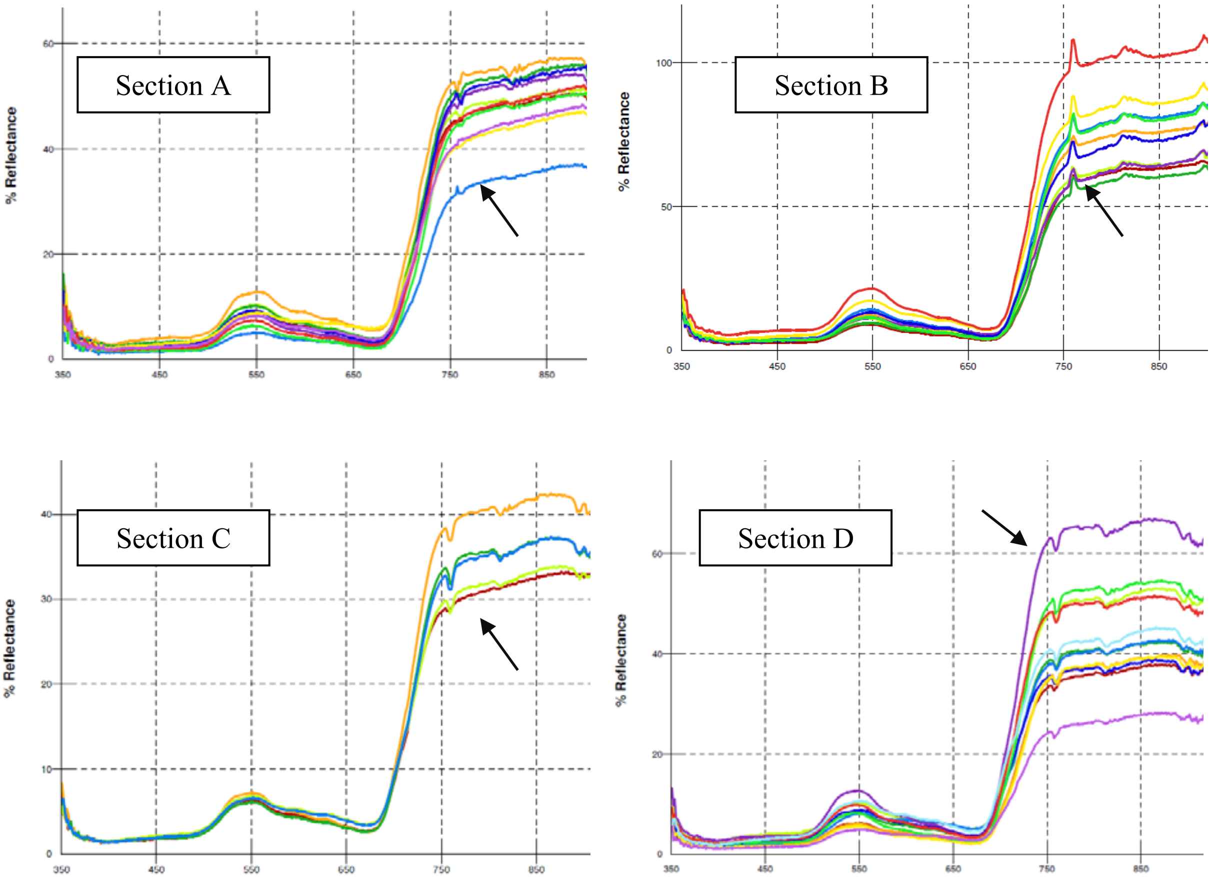

Figure 8: Spectro-radiometric measurements in 05/03/2010. Each diagram corresponds to a cross section (A-D) while the spectral signature indicated with an arrow corresponds to the subsurface geophysical anomaly [15].

2.3. LSU results

The above spectral signatures were used in the LSU algorithm in order to record any stress vegetation similar to the spectroradiometric results over the geophysical anomalies. The LSU algorithm was applied at a multispectral Landsat TM image. Initially, geometric correction was carried out to the satellite image using standard techniques with ground control points and a second order polynomial fit. For this purpose, topographical maps were used at a scale of 1:5000. Then, the conversion of DN values to radiance values was performed and finally reflectance values were calculated. It should be also mentioned that atmospheric correction was also applied using the darkest pixel algorithm [19].

The assumption made for the application of the LSU algorithm, was that the Arkalon locality was fully cultivated with barley crops (without any soil background). This was essential since due to the limited bands (multispectral) of the Landsat image. Therefore two main categories – classes- were classified (healthy and stress vegetation) along with the error parameter. Figure 9 shows the basic steps followed for the LSU application and the abundance results for the three categories (healthy, stress vegetation and error).

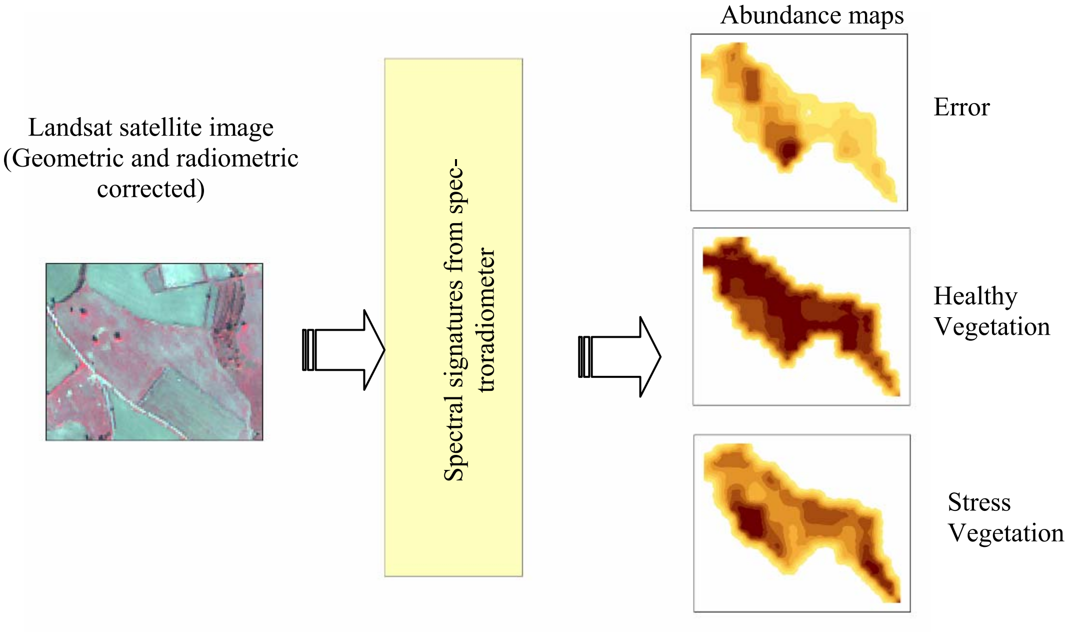

Figure 9: LSU application for the Palaepaphos archaeological site.

The final result of the stress vegetation abundance map was evaluated along with the geophysical survey results. As it is shown in Figure 10, high correlation of the LSU and geophysical anomalies is observed at the southwest corner of the parcel, where a dense cluster of architectural remains was identified through the magnetic and ground penetrating radar surveys. In general, there is a great agreement of the LSU results with geophysical surveys.

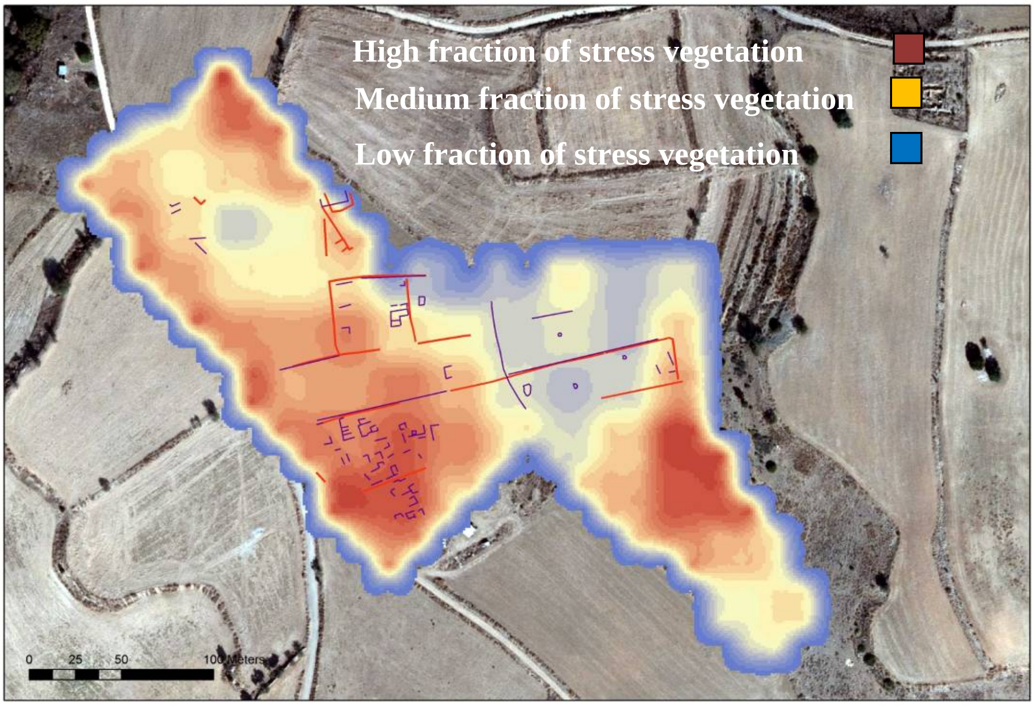

Figure 10: Stress vegetation abundance map with the geophysical results at the Arkalon locality, Palaepaphos archaeological site.

Despite the assumptions for the Arkalon locality, the LSU results were found very promising for archaeological purposes. Indeed the LSU as it is shown in Figure 10, can be used for the detection of buried archaeological remains. Further evaluation of the LSU algorithm was applied to the Thessalian plain.

3. Thessalian plain, north Greece

3.1. Historical background

The Thessalian plain is located in central Greece. The Thessalian plain is considered to be as the primary agricultural area of Greece. In this extensive area several Neolithic settlements/tells called magoules were established from the Early Neolithic period until the Bronze Age (6,000 – 3,000 BC). These settlements are typically low hills of 1–5 meters height above the surrounding area and they mainly consist of loam and mud based materials. Hundreds of magoules are located all over Thessaly and can be found within different kinds of vegetation. However due to the intensive cultivation of the land in the past and their low elevation, a major number of them are not clearly visible from the ground (Figure 11) [8], [9], [12].

Figure 11: Neolithic tells at the Thessalian plain (left). Karatsantagli magoula (middle) and Zerelia magoula (right).

3.2. Previous results

Previous results at the Thessalian plain, contacted by Alexakis et al. [8], [9], have shown that remote sensing techniques can be used for the detection of the Neolithic settlements. Alexakis et al. [8], [9] have used a variety of satellite images (Landsat, ASTER, IKONOS and Hyperion) in order to extract useful archaeological information. Furthermore, recent spectroradiometric measurements taken in several of these magoules, using the GER 1500 spectroradiometer have indicated that each magoula has its own spectral characteristics related to its own morphological characteristics [12]. The study performed by Agapiou et al. [12], has proved that the highest peak of the magoula tends to give high NDVI and SR values (similar to the flat – healthy regions), while the slope of the magoula has lowest NDVI and SR values (and for the other indices as well). A typical spectral signatures profile over a section of a magoula is shown in Figure 12. It was also found out, that promising results can be extracted over the central section of each magoula while the other sections taken in a distance offset from the central one did not indicate any significant differences.

Figure 12: Spectral signature profiles over a magoula (left) and photo during the field campaign using the GER 1500 spectroradiometer (right).

3.3. Vegetation indices

Vegetation indices are mainly derived from reflectance data from the Red and Near Infrared (NIR) bands. They operate by contrasting intense chlorophyll pigment absorption in the red against the high reflectance of leaf mesophyll in the near infrared. The most widely used index is the well-known Normalized Difference Vegetation Index (NDVI) having been used in many different applications and obtained by using the Equation 2.

$$NDVI = (p_{NIR} - p_{red}) / (p_{NIR} + p_{red}) \quad \text{[Eq. 2]}$$

where:

p_{NIR} is the reflectance at near infrared spectrum
p_{red} is the reflectance at red spectrum

In order to improve the results derived from the NDVI method, different radiometric enhancement methods were applied to the final vegetation index product. This type of enhancement, referred as contrast stretching, linearly expands the original digital values of the remotely sensed data into a new distribution of values. By expanding the original input values of the image, the total range of sensitivity of the display device can be utilised. Linear contrast enhancement also makes subtle variations within the data more obvious [20].

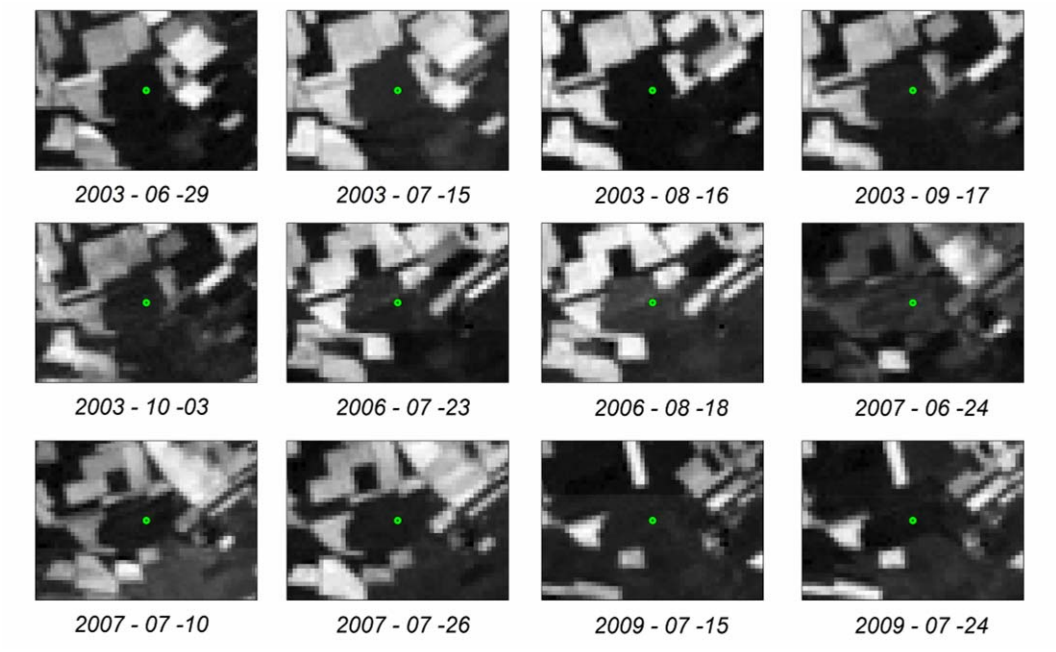

Figure 13: NDVI results for Nikaia 6 (indicated in green circle), archaeological site from several Landsat TM/ETM + images.

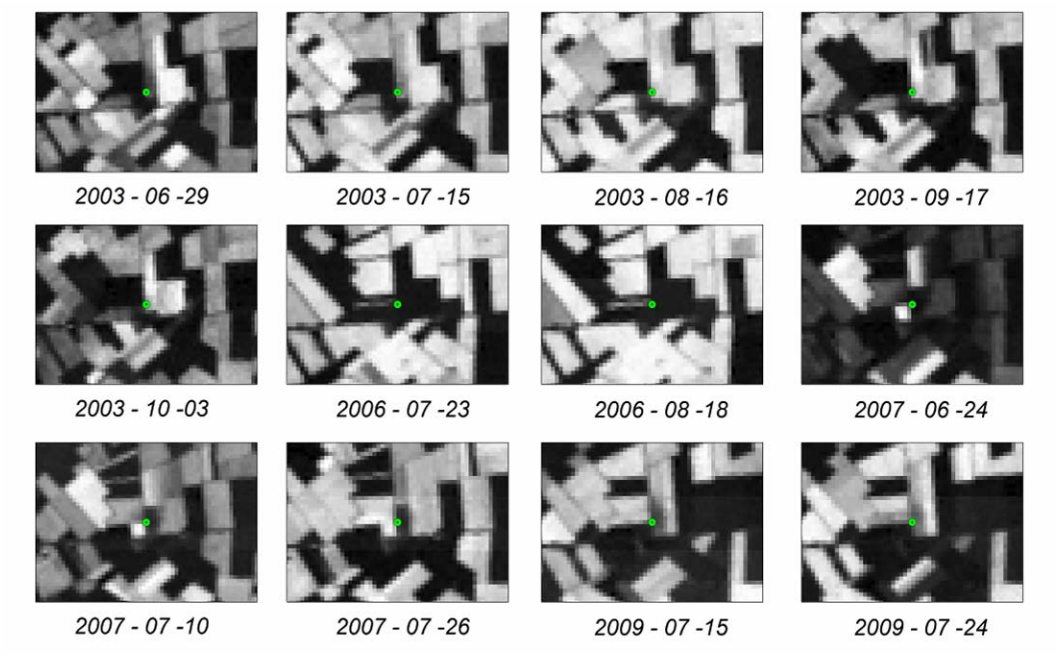

Figure 14: NDVI results for Nikaia 16 (indicated in green circle), archaeological site from several Landsat TM/ETM + images.

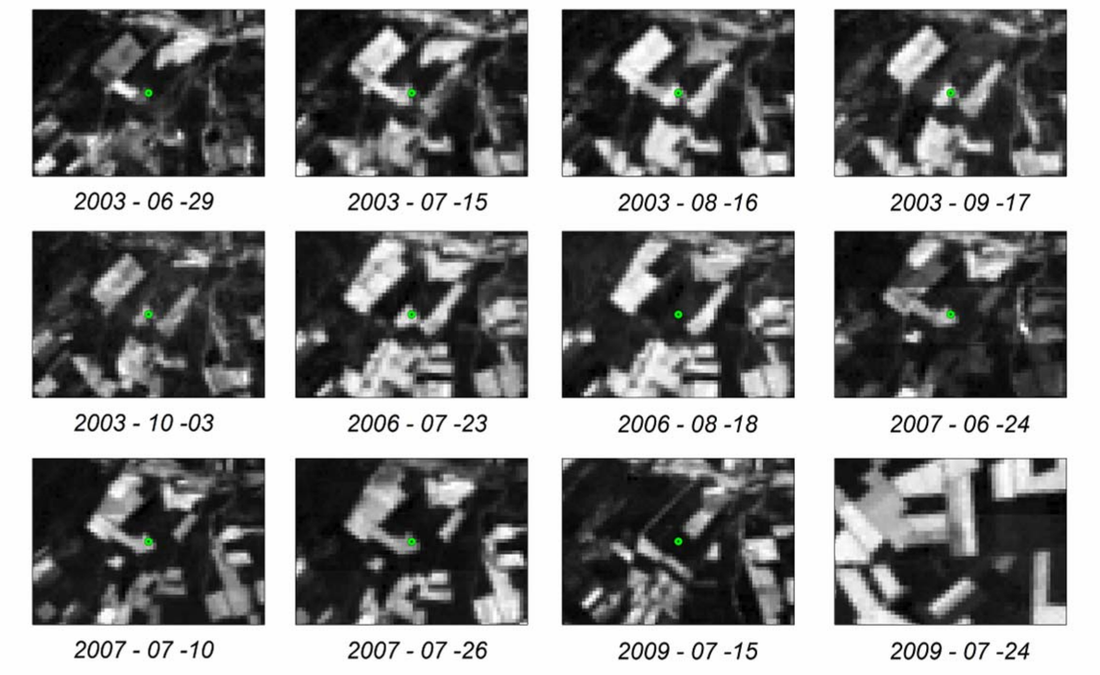

Figure 15: NDVI results for Almyros II (indicated in green circle), archaeological site from several Landsat TM/ETM + images.

As it is shown from Figures 13-15, magoules are difficult to be distinguished using vegetation indices without any radiometric enhancements. Similar conclusions have been also reported by Alexakis et al. [8], [9] regarding the Landsat images. However, local histogram enhancements can identify magoules based on the small difference of NDVI values within the same parcel (Figures 16-17). As Alexakis et al. [8], [9] have shown, vegetation indices can be applied successfully in higher spatial resolution images (e.g. ASTER) for the detection of the Neolithic settlements.

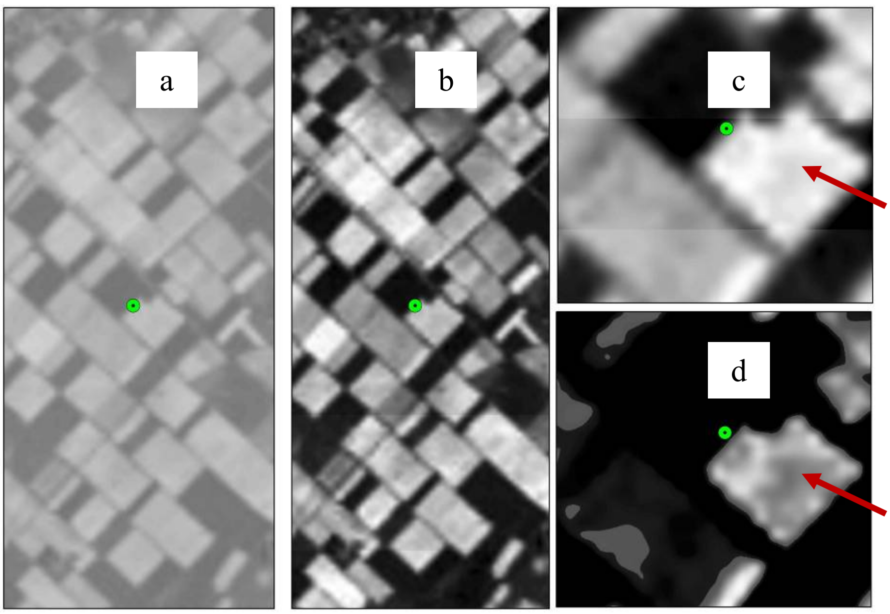

Figure 16: NDVI results for Prodromos II site (in green circle). (a) Raw satellite image without any radiometric enhancements, (b) satellite image with a linear max-min enhancement applied to all image, (c) max-min enhancement

applied to the area around Prodromos II and (d) modified max-min enhancement applied to the area around Prodromos II. The magoula is indicated with the red arrow.

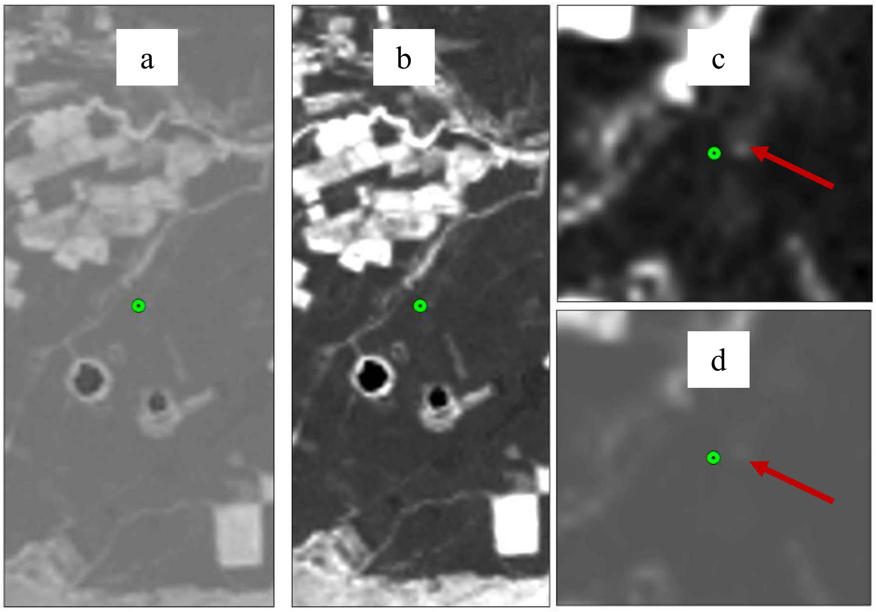

Figure 17: NDVI results for Zerelia site (in green circle). (a) raw satellite image without any radiometric enhancements, (b) satellite image with a linear max-min enhancement applied to all image, (c) max-min enhancement applied to the area around Zerelia and (d) modified max-min enhancement applied to the area around Zerelia. The magoula is indicated with the red arrow.

3.4. Tasseled Cap

Tasseled Cap algorithm (also known as K-T algorithm), as firstly developed by Kauth and Thomas in 1976 [21], was also applied to a series of Landsat TM/ETM+ multispectral images. Tasseled Cap transformation is used to enhance spectral information for Landsat images, and it was specially developed for vegetation studies. The first three bands of the Tasseled Cap algorithm result are characterized as follow:

- band 1: brightness (measure of soil)
- band 2: greenness (measure of vegetation)
- band 3: wetness (interrelationship of soil and canopy moisture)

In detail the Tasseled Cap algorithm is a linear combination of the initial bands of the Landsat image. The first three parameters of the T-K are calculated as shown in Eq. 3:

$$\begin{aligned}
Brightness &= 0.3037(TM1) + 0.2793(TM2) + .4743(TM3) + 0.5585(TM4) + 0.5082(TM5) + 0.1863(TM7) \\
Greenness &= -0.2848(TM1) - 0.2435(TM2) - 0.5436(TM3) + 0.7243(TM4) + 0.0840(TM5) - 0.1800(TM7) \\
Wetness &= 0.1509(TM1) + 0.1973(TM2) + 0.3279(TM3) + 0.3406(TM4) - 0.7112(TM5) - 0.4572(TM7) \quad \text{[Eq. 3]}
\end{aligned}$$

Tasseled Cap results are presented in Figure 18. The results are very similar to the NDVI algorithm: magoules were able to be detected only after local enhancements.

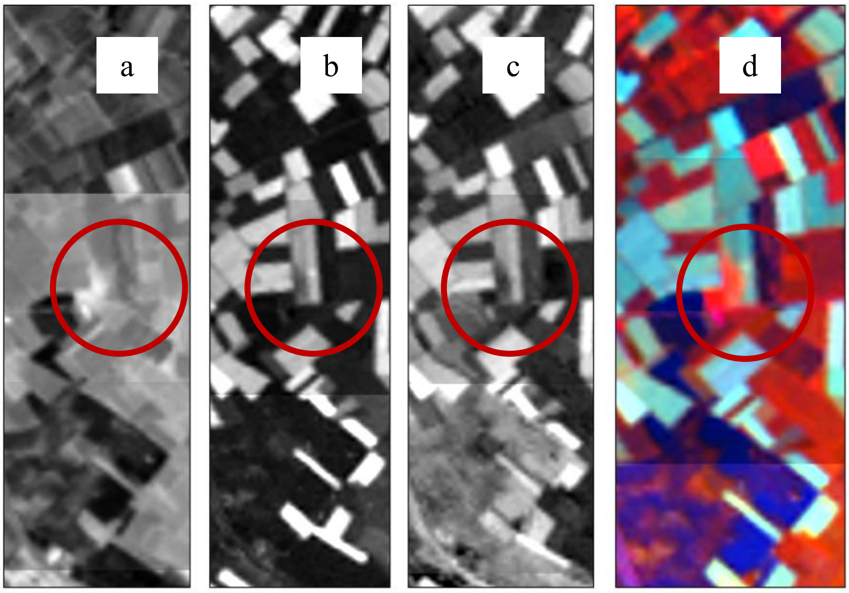

Figure 18: Tasseled Cap results for Nikaia 16 site (in red circle), (a) Brightness, (b) greenness, (c) wetness and (d) RGB of the first three components of the T-K algorithm.

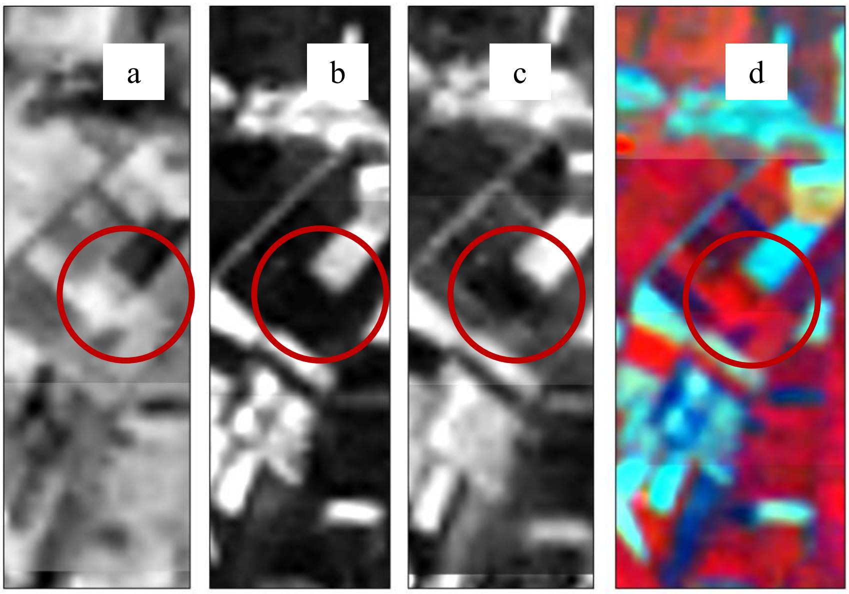

Figure 19: Tasseled Cap results for Almyros II site (in red circle), (a) Brightness, (b) greenness, (c) wetness and (d) RGB of the first three components of the T-K algorithm.

3.5. LSU

LSU was applied to a series of Landsat images in order to identify its potential use for the detection of the Neolithic settlements. In contrast to the Palaepaphos case study where the endmember spectra were collected using ground spectroradiometric measurements, in the case of the Neolithic tells this was not possible since there was no satellite overpass during the in-situ campaign. Therefore, the endmember spectra were collected from the satellite images. Special attention was given in order to detect –as much as possible- “pure pixels” in the image. An important endmember spectra was the vegetation signature over known archaeological sites. After several efforts the results have be able to spot some magoules (Figure 20). Indeed as it is shown in Figure 20, LSU algorithm was able to classify the Almyros II site as an area with high stress vegetation fraction, despite the fact that the site was fully cultivated. However other magoules (e.g. Zerelia) were not able to be detected with the LSU algorithm (Figure 21).

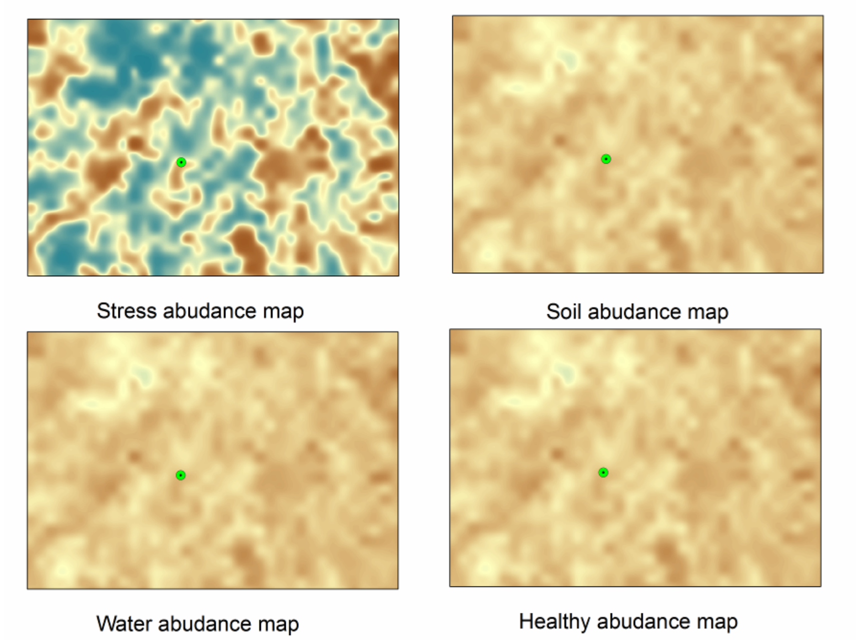

Figure 20: LSU results for Almyros II site. Different abundance maps are shown. Special attention is given to the Stress abundance map.

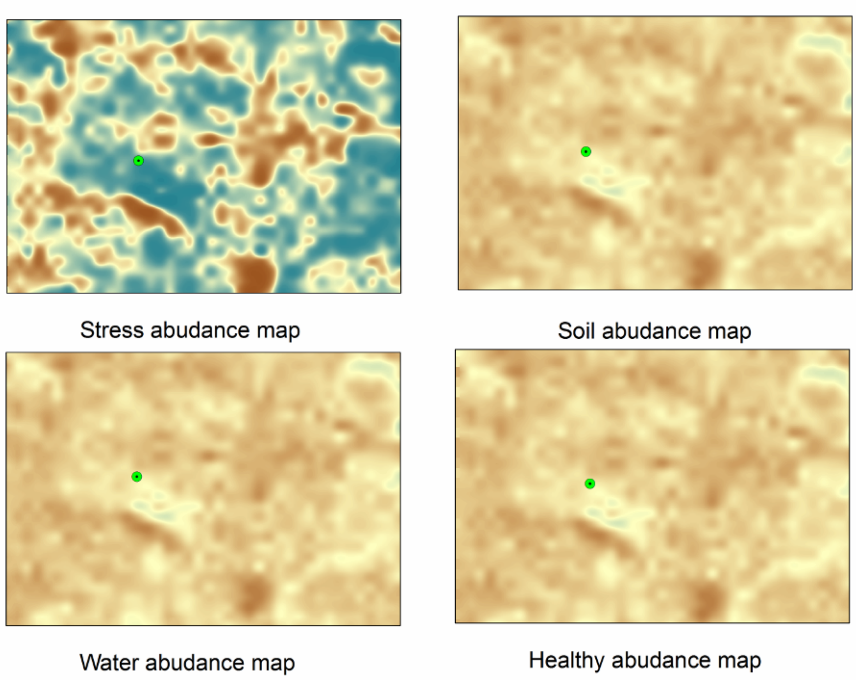

Figure 21: LSU results for Zerelia site. Different abundance maps are shown. Special attention is given to the Stress abundance map.

4. Conclusions

This paper presents the results from two archaeological sites in Cyprus and Greece. In these sites different remote sensing techniques have been evaluated. In the Palaepaphos case study, further to ground spectroradiometric and geophysical surveys, LSU technique was also applied. The results were found very promising since LSU results were compatible with the previous ground techniques. Ground spectroradiometric measurements were taken during the satellite overpass, and therefore these ground spectra were used as the "Endmember spectra" for the LSU application.

For the Thessalian plain, vegetation indices and T-K algorithms were applied in a series of multispectral Landsat TM and ETM+ images. The results have shown that the magoules were able to be detected only after local enhancement. Previous studies [8], [9] have come to the same conclusion for Landsat images. Satellite images with higher spatial resolution are possible to give better results.

LSU was applied experimentally in this study in an effort to evaluate its potential for archaeological purposes. Although some limitations of this approach were recorded, some promising results were also found. Future work will focused to the use of LSU method in higher spatial resolution satellite images along with ground measurements of pure pixels. This will enable a full evaluation of this approach. The potential of the LSU algorithm is fundamental for remote sensing archaeology since LSU can be applied in cases when the spatial resolution of the satellite image is inadequate for archaeological investigations.

Moreover, in the near future, nonlinear processes will be also evaluated. Therefore non linear spectral unmixing techniques will be tested for the detection of the Neolithic settlements and other subtle archaeological sites.

Acknowledgements

These results are part of the PhD dissertation of Mr. Athos Agapiou. The authors would like to express their appreciation to the Alexander Onassis Foundation for funding the PhD study. Also thanks are given to the Remote Sensing Laboratory of the Department of Civil Engineering & Geomatics at the Cyprus University of Technology for the support (http://www.cut.ac.cy).

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