HYPERSPECTRAL IMAGING IN PRESERVATION OF CROATIA'S HISTORIC TREES: A CASE STUDY OF DEDEK OAK IN MAKSIMIR PARK

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ABSTRACT:

This study focuses on the application of hyperspectral imaging techniques for the genetic preservation of historic trees, specifically investigating the 600-year-old "Dedek" Oak in Maksimir Park, Croatia. The research aims to contribute to the conservation of Croatia's natural heritage and underscore the potential of hyperspectral imaging in tree preservation.

The Croatian Forest Research Institute has been actively involved in preserving the pedunculate oak trees, recognizing their cultural and ecological significance. Efforts have been made to cultivate seedlings from the original genetic material, thereby preventing the loss of valuable genes and ensuring their long-term preservation.

Spectral signatures of "Dedek" Oak and its clones were captured using high-performance hyperspectral push broom cameras, including the HySpex VNIR-1800 and SWIR-384. Spectral camera scanning was conducted in the field and laboratory. The comparative analysis of the spectral samples revealed unique characteristics and demonstrated the effectiveness of hyperspectral imaging in studying historic trees for preservation purposes.

The spectral signatures of vegetation display dynamic characteristics in terms of spectral resolution. Collecting and documenting these signatures is considerably more challenging, and their integration into spectral libraries should be approached with careful consideration. There are several spectral libraries that are organized by chapters and consist of samples that have a sufficient number of analysis and documentation to determine the quality of the spectrum.

In this study, spectral signatures of pedunculate oak (*Quercus robur L.*) called Dedek and its clones were singled out. The objective of this research was to establish a foundation for a spectral library that would facilitate future research on the application of hyperspectral scanners for detecting protected tree species and their clones, all for the purpose of preservation of the genetic diversity of protected trees in Croatia.

The findings of this research contribute to the conservation of Croatia's natural heritage by providing valuable insights into the genetic preservation of the 600-year-old "Dedek" Oak. Also, determining the spectral signatures of clones can help us with the identification of specific tree species (especially during aerial imaging, which is planned to be conducted in the future).

In conclusion, this research showcases the importance of preserving historic trees and the potential of hyperspectral imaging as a valuable tool for genetic preservation efforts. The study's outcomes contribute to the long-term conservation of Croatia's natural heritage and provide a foundation for future research in the field of tree preservation and spectral library inception.

1. INTRODUCTION

Pedunculate oak in Croatia (*Quercus robur L.*) plays a crucial role in the formation of ecologically significant forest communities. These communities serve as habitats for numerous endangered and/or protected plant and animal species, highlighting the oak's ecological importance. Additionally, the pedunculate oak stands out as one of the most valuable deciduous tree species in Europe. Its presence contributes to the biodiversity of forests and holds immense ecological and social value (Ducousso and Bordacs, 2003). Moreover, pedunculate oak forests have a significant ecological impact, particularly in terms of erosion control and hydrological regulation (Babić, 2016).

The Croatian Forest Research Institute has been actively involved in preserving the pedunculate oak trees, recognizing their cultural and ecological significance. Efforts have been made to cultivate seedlings from the original genetic material, thereby preventing the loss of valuable genes and ensuring their long-term preservation.

There are several protected trees in the Republic of Croatia:

Common name: "Gupčeva lipa" (*Tilia platyphyllos Scop.*)
Location: Gornja Stubica, Krapina-Zagorje County
Protection: Natural Monument - rare tree specimen (1957)

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Description: 9m tall with a 4.90m trunk circumference and 1.57m breast diameter. A natural rarity with distinctive appearance and imposing branches.

Common name: "Jaskanska bukva" (*Fagus sylvatica L.*)
Location: Erdödy Manor Park, Jastrebarsko, Zagreb County
Protection: Preservation of the Genome project (2013)
Description: Severely damaged in November 2013 by cyclone Teodor. Successful cloning preserved its genes for the future.

Common name: "Hrast Dedek" (*Quercus robur L.*)
Location: Maksimir Park, City of Zagreb
Protection: Not officially protected, but recognized for genetic value
Description: Approximately 600 years old, the oldest tree in Maksimir Park. Impressive dimensions and solitary growth. Saplings propagated from its scions exist.

Common name: "Hrast lužnjak" (*Quercus robur L.*)
Location: Prašnik, Brod-Posavina County
Protection: Special Reserve of Forest Vegetation (1965)
Description: Area of preserved Slavonian pedunculate oak forest. Average age of trees: 150-300 years, with heights up to 40m. The only remaining old growth pedunculate oak forest in Slavonia (Lanšćak et al., 2019).

Park Maksimir, where Dedek is located, was founded at the end of 18th century as the first public park in Southeast Europe, and today it is the largest city park and the most important landscape park of Croatia (Vitasović Kosić and Aničić, 2005). It is in the category of forest park, which differs from economic forests only for the purpose of management, which is primarily the maintenance and improvement of non-market forest functions (Ostrogović et al., 2010). Due to its purpose and position, the forest park requires special and more intensive treatment due to the usual interventions of care, renovation, and maintenance (Matić and Prpić, 1997). Since its inception, the forest park has undergone numerous changes, but it remains a unique set of natural forest elements.

To maintain the stability of the forest ecosystem, it is necessary to perform various regeneration and care operations and maintain the forest in optimal condition (Zagoranski et al., 2018). The health of the trees has deteriorated due to changes in the environment and the age of the forest. The health status of the tree can be monitored directly by field observation using the classical forestry terrestrial method (Prpić et al., 1988, Potočić and Seletković, 2011), remote sensing methods, most often by interpreting infrared (CIR) aerial imaging (Kalafadžić and Kušan, 1990, Pernar, 1994) and laboratory, terrestrial or aero hyperspectral imaging.

There has been a significant shift in recent years, with hyperspectral imaging becoming increasingly available for wider applications (Lu et al., 2020, Stuart et al., 2022). This opens new opportunities for exploiting hyperspectral data in precision agriculture, as it provides valuable insights into crop health, nutrient status, stress levels and other relevant parameters, facilitating more informed precision agriculture decision-making. The increasing availability of hyperspectral imaging technology presents an opportunity to exploit its potential to optimize agricultural practices. Integrating hyperspectral data into precision agriculture systems can improve crop management strategies, optimize resource allocation, and improve overall productivity and sustainability. Hyperspectral imaging shows promise as a valuable tool for monitoring crop dynamics in precision agriculture. With its increasing availability, it is expected to play an increasing role in supporting sustainable agricultural practices and maximizing productivity in the future. Similar is being used in forestry applications (Goodenough et al., 2012, Tusa et al., 2019, Saarinen et al., 2018, Krtalić et al., 2021).

In recent decades, we have witnessed intense change in the world we live in, both in lifestyles and climate change. Temperature extremes, sudden precipitation out of season and long dry and rainy periods are becoming more frequent. These changes have a negative impact on vegetation often resulting in high mortality of protected trees that have long been eroded by the "ravages of time" (Lanšćak et al., 2019).

Pedunculate oak (*Quercus robur*) and sessile oak (*Quercus petraea*) are economically and environmentally significant species of deciduous trees that are widespread throughout Europe. In the Republic of Croatia, pedunculate oak has great value and is considered one of the most important species, especially in the areas of floodplains of the largest rivers. The largest complete pedunculate oak forest in Croatia and one of the largest in Europe is located in the area of Spačva and covers an area of 40.000 ha. Pedunculate oak forests in Croatia have great economic significance, but at the same time an important ecological and social role (Ballian et al., 2010).

By breeding clones, a tree of the same genetic abundance as the mother tree is obtained. One of the guiding principles in the preparation of this paper was to collect spectral signatures of mother trees, their clones, and other trees of the same species with the assumption that their spectral response should be similar.

2. METHODS AND MATERIALS

To obtain spectral information of the objects electro-optical remote sensing is used. It involves the acquisition of information about an object or scene without coming into physical contact with it. This is achieved by exploiting the fact that the materials comprising the various objects in a scene reflect, absorb, and emit electromagnetic radiation in ways characteristic to their molecular composition and shape. If the radiation arriving at the sensor is measured at each wavelength over a sufficiently broad spectral band, the resulting spectral signature, or simply spectrum, can be used (in principle) to uniquely characterize and identify any given material. The field of spectroscopy is concerned with the measurement, analysis, and interpretation of such spectra. Combining spectroscopy with methods to acquire spectral information over large areas is known as imaging spectroscopy (Shaw and Manolakis, 2002).

Hyperspectral imaging is a spectroscopic technique that allows information to be collected for several hundred wavelengths at different spatial positions. Radiation reaching the surface of the leaf can be reflected, absorbed, or transmitted. The nature and proportions of reflection, absorption and transmission depend on the wavelength of radiation, the incidence angle, the surface roughness, as well as the optical properties and biochemical content (Olujić, 2002, Mateen et al., 2018).

The images can be visualised as a 3-dimensional dataset with two spatial and one spectral dimension and the data set is therefore often referred to as an image cube. Originally, raw hyperspectral data are combined in an image cube with spatial, temporal, and spectral dimension, after the imaging characteristic of the hyperspectral sensor (mostly push-broom scanner), and they have to be transformed to geocoded hyperspectral cubes for all further spatial analysis of hyperspectral data. There are several methods to transform raw hyperspectral data (raw cube) into

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geocoded one. Because of imaging geometry of the hyperspectral sensor (push-broom scanner), only the parametric geocoding methods can be applied directly (Miljković and Gajski, 2016).

The reflectance of leaves is the result of multiple interactions between incoming irradiation and biophysical (e.g., leaf surface, tissue structure) and biochemical characteristics (e.g., content of pigments and water) of plants (Gitelson et al., 2003).

Several studies have described the prospects of sensing leaf reflectance in the visible (VIS, 400-700 nm), near infrared (NIR, 700-1000 nm) and short wave infrared (SWIR, 1000-2500 nm) for detecting changes in plant vitality with emphasis on fungal plant diseases using non-imaging spectroradiometers (Rumpf et al., 2010, Mahlein et al., 2010, Mahlein et al., 2012).

Variance analysis, discriminatory analysis and multiple testing for the investigated properties, grouped by country of origin (Croatia, Bosnia and Herzegovina, Serbia and Montenegro), indicate the existence of statistically significant differences between the studied populations, i.e., that the investigated material from each country forms a separate group (Ballian et al., 2010). The use of HSI can replace the previous traditional methods and the analysis of clones that have been grown in forestry institutes replaces the need to go to the field and take samples. Furthermore, hyperspectral imaging provides an effective method for identifying areas with high and low wood properties, allowing tree growers to make more informed decisions about how to grow. NIR shows better results in predicting physical properties while HSI better identifies variations in wood properties (Viet et al., 2021). These properties even allowed the possibility to distinguish vine leaves of different clones of the Cabernet Sauvignon variety (*V. vinifera L.*) using PLS analysis of data obtained by hyperspectral imaging in a narrow range of visible and near infrared spectrum. This narrow range, which includes strong absorption of chlorophyll and red edge, is used to facilitate the development of affordable specialized spectroscopes (Fernandes et al., 2015).

The red edge, a distinct characteristic of plants, arises from their optical properties. High internal leaf scattering leads to significant near-infrared reflectance, while chlorophyll absorption results in low red reflectance. This unique feature allows for differentiation between live vegetation and other remote sensing targets. The red edge forms the foundation for vegetation identification methods based on combined red and infrared radiances, even though it is not directly measured (Horler et al., 1983).

2.1 Sample collection

The canopy of the protected Pedunculate Oak tree Dedek was captured in Maksimir Park Forest (Figure 1). Maksimir Park is a unique architectural park heritage site of the City of Zagreb and the Republic of Croatia. It was established at the southern edges of Medvednica Mountain in the late 18th and early 19th centuries, resulting from the clearing of the native Pedunculate Oak and Common Hornbeam forest. The first protection of Maksimir Park dates to 1948, and it covers an area of 316 hectares in Zagreb (Taylor, 2006).

Figure 1. Dedek Oak in Maksimir Park.

The canopy of Dedek in the park was captured using the HySpex hyperspectral cameras. Their specifications can be found in Figure 2.

	VNIR - 1800	SWIR - 384
Spectral range	400 – 1000 nm	930-2500 nm
Spatial pixels	1800	384
Spectral channels	186	288
Spectral sampling	3.26 nm	5.45 nm
FOV*	17°	16°
Pixel FOV across/along*	0.16/0.32 mrad	0.73/0.73 mrad
Bit resolution	16 bit	16 bit
Noise floor	2.4 e-	150 e-
Dynamic range	20000	7500
Peak SNR (at full resolution)	> 255	> 1100
Max speed (at full resolution)	260 fps	400 fps
Keystone	less than 5%	less than 5%
SMILE	less than 10%	less than 10%

Figure 2. Specifications of used hyperspectral cameras.

The Dedek's clones were captured at the Croatian Forest Research Institute in Jastrebarsko by field setup of HySpex sensors. Since both Dedek and the clones are legally protected (it is forbidden to collect branches or leaves), it was not possible to take leaf samples to the laboratory and perform hyperspectral imaging under ideal conditions. The same HySpex sensors were used to capture Dedek and the clones, under approximately the same atmospheric conditions.

For data validation, other samples of Pedunculate Oak leaves (*Quercus robur* and *Quercus robur Fastigiata*) were captured in laboratory settings. Their samples were taken from the Zagreb area.

2.2 Data processing

The data processing was performed in multiple software tools. The raw data obtained from field and laboratory measurements needed to be converted from a raw format to radiance, which was accomplished using the HySpexRAD software.

Some of the obtained hyperspectral images of all taken samples after being converted into radiance are shown in Figures 3 – 8.

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Figure 3. SWIR image of Dedek Oak.

Figure 4. VNIR image of Dedek Oak.

Figure 5. SWIR image of clones (from left to right: three clones of Gupčeva lipa and two clones of Dedek Oak).

Figure 6. VNIR image of clones (from left to right: three clones of Gupčeva lipa and two clones of Dedek Oak).

Figure 7. SWIR image of other samples of Pedunculate Oaks (left: *Quercus Robur Fastigiata*; right: *Quercus Robur*).

Figure 8. VNIR image of other samples of Pedunculate Oaks (left: *Quercus Robur Fastigiata*; right: *Quercus Robur*).

The obtained radiance data was then processed in Breeze software, where image segmentation and classification were conducted.

Image segmentation was performed using the PLS regression method to determine the optimal number of components that capture the most relevant spectral information related to the target variables. Partial least squares were used to develop classifiers that provided clone classes. This method constructs a model that transforms the independent variables, in this case, leaf radiance values, into a dependent variable. It transforms the independent variables into a new set of variables that maximally explain the covariance between the independent and dependent variables (Geladi and Kowalski, 1986).

To conduct spectral analysis of variations, a PCA model was generated using all the pixel values in all bands.

It was necessary to create a model pattern to remove background pixels and automatically identify objects. Specific spectral bands (of different wavelengths) were selected and included in the model. By default, all wavelengths are included, except for the first and last bands, as they are usually noisier. In Breeze, 4% of bands are turned off by default.

A mosaic of all images was generated, and a PCA model was created using all the pixels in the mosaic. To select an area containing only Dedek Oak pixels, an area within one of the objects is selected. Then a critical distance threshold was set, which determines whether pixels are considered patterns or not based on their distance from the pattern model. Next, object samples were determined in the images after applying model sampling and background pixel removal. Only those samples that were in the area of undisturbed reflection (areas not in shadow and leaves facing the source of electromagnetic radiation) were included. A PCA model was then created based on the average spectrum for each sample.

Finally, the average spectrum for each sample and the assigned class type was used to train classification models.

3. EXPERIMENTAL RESULTS

In this paper, only the experimental results of radian processing, which were made from raw bands, are presented. Given that the reflectance of the originals and clones should be consistent, an attempt was made to detect possible differences in the responses of originals and clones through radiance analysis. Mean values of the spectral signatures in the visible near infrared range (VNIR: 400 – 1000 nm) and short infrared range (SWIR: 930 – 2500 nm) were determined and their graphical representations can be seen in Figure 9.

The spectral reflection inherent in the leaves of plants is determined by the absorption and scattering that occurs within the leaf (Grant, 1987). In the visible range (VIS: 400 – 700 nm), leaf pigments are the main factors responsible for leaf reflection, while in the near-infrared (NIR: 700 – 1350 nm) and short infrared (SWIR: 1400 – 3000 nm) range, the reflex signature of the leaves is determined by structural processes (leaf morphology) and the water content of the leaf (Peñuelas et al., 1993). The transition from low reflection in the VIS range to high reflection in the NIR range is called the red border (Collins, 1978). In published papers, intrinsic differences in pigment content among clones of a particular species have been reported (Taylor et al., 1992, Conforto et al., 2011, Lin et al., 2011).

Based on the graphs shown in Figure 9, one could conclude that there is similarity of the response between Dedek and its clones in the VNIR range (which is expected since they are the same species). But there are differences in the SWIR range, specifically in the spectral regions of 1350 – 1500 nm and 1800 – 2000 nm. In the following research, it will be determined whether there is a possibility of distinguishing the original from the clone in a similar way (unfortunately, until the end of this article, no other clones were available to us).

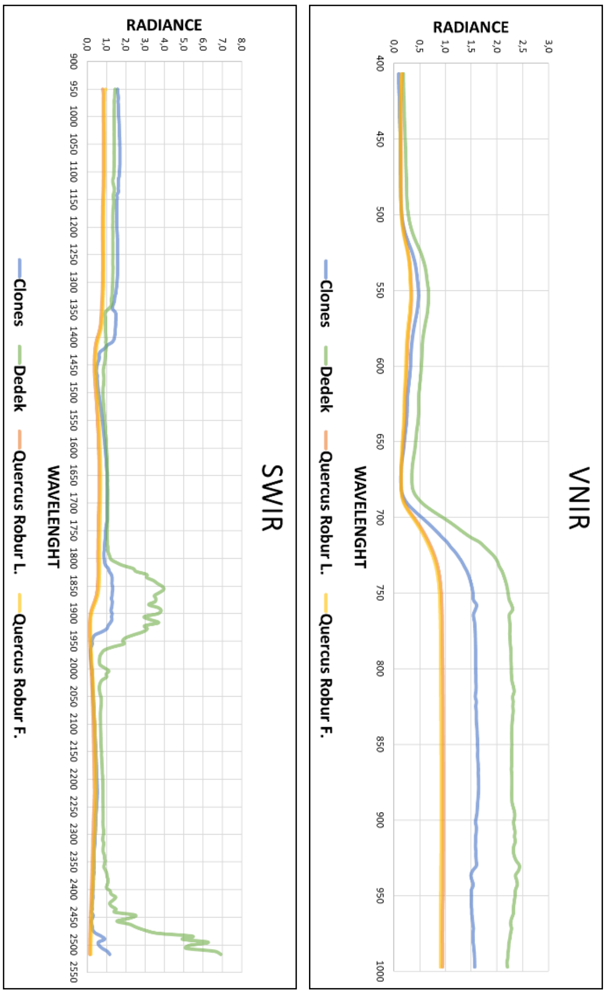

Figure 9. Obtained spectral signatures in the SWIR (left) and the VNIR (right) range.

It is planned to create and store a physical database of clones of a large number of different individuals throughout the Republic of Croatia. In other words, the clones that were tested, both spectrally and biologically, will be stored in one place.

In addition, it is also planned to create and store a library of spectral responses of a large number of different individuals in the territory of the entire Republic of Croatia, through radiance and later reflectance. Such samples will serve to find and define the area populated by a certain species, as well as to define the health condition in which it is. The clone database can be used by biologists to manipulate the health status of individual plants. They can be exposed to different pests and plant diseases and their spectral responses monitored. This way, a critical stage of the plant can be found where it could still be helped by getting rid of pests or applying cure to diseased plants. Such a preventive approach to the health problem of plant individuals (or larger groups, forests) aims to contribute to the monitoring and conservation of Croatia's natural heritage.

4. CONCLUSION

It is a well-known fact that the use of hyperspectral sensors has great potential in monitoring the state of plant species. This paper presents the method of using clones of certain plant species for spectral analysis and announced biological manipulations of them, for the purpose of creating a library of healthy and “diseased” spectral samples. Both will be used to locate plant species. The first is for mapping the area populated by these plant species, and the second is for the purpose identifying plant individuals in poor condition that can be helped and their condition improved. Plant clones can be used to create spectral libraries of plant species they represent. Such clones (together with the soil in which the original plant grows) can be stored in a physical database of clones which is the source of spectral responses (samples) and on which biological experiments can be carried out, after which the spectral responses are retaken.

A discrepancy was observed in the spectral responses of the original plant and its clone in the spectral areas 1350 – 1500 nm and 1800 – 2000 nm, between the calculated radian bands. In subsequent research, it will be examined whether this phenomenon is repeated on other pairs of plants (original and clone). The results of this research aim to contribute to easier inventorying, monitoring, analysis, and preservation of the natural heritage of the Republic of Croatia, especially some ancient or legally protected plant species.

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