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Detección de síntomas tempranos de decaimiento en bosques abiertos de encinas mediante imágenes satelitales de muy alta resolución espacial

Martín, M. Pilar [1] **González-Cascón, Rosario** [2] **Burchard-Levine, Vicente** [1] **Casillas-Martínez, Lucía** [1] **Pacheco-Labrador, Javier** [1] **Bareth, Georg** [3]

[1] Laboratorio de Espectro-radiometría y Teledetección Ambiental (SpecLab-CSIC), España

[2] Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA-CSIC), España

[3] Institute of Geography. University of Cologne, Alemania

ORCID: Martín 0000-0002-5563-8461 González-Cascón 0000-0003-3468-0967 Burchard-Levine 0000-0003-0222-8706 Casillas-Martínez 0009-0002-5306-9776 Pacheco-Labrador 0000-0003-3401-7081

Correspondencia: mpilar.martin@csic.es cascon@inia.csic.es vicente.burchard@csic.es lucia.casillas@csic.es javier.pacheco@csic.es g.baret@uni-koeln.de

RESUMEN

El seguimiento de la salud y productividad de los ecosistemas forestales es posible a partir de un conjunto muy diverso de técnicas que facilitan información a distintas escalas temporales y espaciales. Sin embargo, la integración de estas técnicas aún no se ha implantado de forma eficaz en redes de ámbito global. El proyecto SensOFOREST, en el que se enmarca este estudio, contribuye a la red europea *"ForestWard Observatory"* mediante la implementación de un sistema integrado de observación (SIO) compuesto por sensores terrestres equipados para la transmisión en tiempo real, así como datos multiescalares de teledetección (in situ, drones y satélites). El proyecto se centra en áreas de estudio representativas de dehesas de encina, donde la estructura de la vegetación supone un reto para el estudio del arbolado con imágenes de satélite. En este trabajo se describe la metodología y objetivos generales del proyecto y se presentan algunos resultados de las campañas experimentales realizadas en septiembre de 2024 y julio de 2025 en la estación experimental de Majadas de Tiétar (Cáceres). Los datos biofísicos y espectrales recopilados en estas campañas demuestran el potencial de las imágenes de satélite de muy alta resolución espacial Pléiades Neo para detectar síntomas tempranos de decaimiento, como la pérdida de masa foliar, en encinas potencialmente afectadas por patógenos presentes en el suelo como *Phytophthora cinnamomi.*

Palabras clave: *Quercus ilex, salud forestal, Pleiades Neo, defoliación, pigmentos*

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Detección de síntomas tempranos de decaimiento en bosques abiertos de encinas mediante imágenes satelitales de muy alta resolución espacial

Martín, M. Pilar [1], González-Cascón, Rosario [2], Burchard-Levine, Vicente [1], Casillas-Martínez, Lucía [1], Pacheco-Labrador, Javier [1], Bareth, Georg [3]

[1] Laboratorio de Espectro-radiometría y Teledetección Ambiental (SpecLab-CSIC), España.
0000-0002-5563-8461, mpilar.martin@csic.es.
0000-0003-0222-8706, vicente.burchard@csic.es.
0009-0002-5306-9776, lucia.casillas@csic.es.
0000-0003-3401-7081, javier.pacheco@csic.es.

[2] Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA-CSIC), España.
0000-0003-3468-0967, cascon@inia.csic.es.

[3] Institute of Geography. University of Cologne, Alemania.
0000-0000-0000-0001, g.baret@uni-koeln.de.

Resumen: El seguimiento de la salud y productividad de los ecosistemas forestales es posible a partir de un conjunto muy diverso de técnicas que facilitan información a distintas escalas temporales y espaciales. Sin embargo, la integración de estas técnicas aún no se ha implantado de forma eficaz en redes de ámbito global. El proyecto SensOFOREST, en el que se enmarca este estudio, contribuye a la red europea "ForestWard Observatory" mediante la implementación de un sistema integrado de observación (SIO) compuesto por sensores terrestres equipados para la transmisión en tiempo real, así como datos multiescalares de teledetección (in situ, drones y satélites). El proyecto se centra en áreas de estudio representativas de dehesas de encina, donde la estructura de la vegetación supone un reto para el estudio del arbolado con imágenes de satélite. En este trabajo se describe la metodología y objetivos generales del proyecto y se presentan algunos resultados de las campañas experimentales realizadas en septiembre de 2024 y julio de 2025 en la estación experimental de Majadas de Tiétar (Cáceres). Los datos biofísicos y espectrales recopilados en estas campañas demuestran el potencial de las imágenes de satélite de muy alta resolución espacial Pléiades Neo para detectar síntomas tempranos de decaimiento, como la pérdida de masa foliar, en encinas potencialmente afectadas por patógenos presentes en el suelo como *Phytophthora cinnamomi*.

Palabras clave: Quercus ilex, salud forestal, Pléiades Neo, defoliación, pigmentos

Monitoring early decay symptoms in holm oak open forests using very high-resolution satellite imagery

***Abstract**: Monitoring the health and productivity of forest ecosystems is possible using a wide range of techniques that provide information at different temporal and spatial scales. However, the integration of these techniques has not yet been effectively implemented in global networks. The SensOFOREST project, under which this study is being conducted, contributes to the European ForestWard Observatory network through the implementation of an integrated observing system (IOS) consisting of terrestrial sensors equipped for real-time transmission, as well as multiscale remote sensing data (in situ, drones, and satellites). The project focuses on areas representative of holm oak open forest, where the vegetation structure poses a challenge for the study of tree cover using satellite images. This work describes the objectives and methodology of the project and presents the preliminary results of the experimental campaigns carried out in September 2024 and July 2025 at Majadas de Tiétar research station (Cáceres). The biophysical and spectral data collected in these campaigns demonstrate the potential of Pléiades Neo very high spatial resolution satellite imagery to monitor early decay symptoms, as defoliation, in holm oak trees potentially affected by of soil-borne pathogens such as Phytophthora cinnamomi.*

Keywords: *Quercus ilex, forest health, Pléiades Neo images, defoliation, pigments*

1. INTRODUCTION

Open forests or wooded grassland ecosystems cover large areas of Mediterranean Europe and are considered hotspots for climate change and biodiversity (Cos *et al*., 2022). They are vital for livestock feed and play a key role in food security in some regions of the planet. They are recently gaining importance as resilient systems because they provide an effective synergy between climate change adaptation and mitigation (Hernández-Morcillo *et al*., 2018). Therefore, these ecosystems are likely to gain importance in the context of climate change adaptation in many regions that are predicted to experience a decline in water availability and an increase in water demand, as well as more severe and prolonged droughts. *Quercus Ilex* L., the dominant species in the Mediterranean open forest, is seriously threatened by several factors, such as increased pathogen's outbreaks or the intensification of extreme weather events which are likely to contribute to its decline. Therefore, it is crucial to monitor how climate change affects the health, growth, and productivity of this forest species. Remote sensing could be a suitable tool for this purpose, but in practice, open forests represent a limitation in Earth observation capabilities from satellite platforms and a serious challenge for the remote sensing and modeling scientific communities. This is because these ecosystems are characterized by complex horizontal and vertical structures where tree and herbaceous vegetation are mixed with different phenological dynamics determined by factors such as drought, grazing, and land use changes. The spectral mixture of all these signals in the same pixel makes it difficult to characterize the individual components. All these factors contribute to making these ecosystems intrinsically difficult to monitor with conventional satellite imagery.

Ground-based automated sensors offering high temporal resolution, combined with very high-spatial resolution data collected by new generation of satellites, including hiperespectral capabilities such as those of the Pixxel hyperspectral imaging constellation (https://www.pixxel.space/hyperspectral-imagery), provide extremely useful complementary information for characterizing the different components of complex ecosystem. These new technological opportunities will facilitate understanding of how these open forests function, assess their response to climate change, and enable the design of management strategies to ensure their sustainability.

We present here the preliminary results obtained in the experimental campaigns undertaken in September 2024 and July 2025 in the context of the SensOFOREST project. This project aims to contribute to the ForestWard Observatory (https://forwards-project.eu/), a monitoring and assessment network that will help demonstrate the impact of climate change on European forests. SensOFOREST will exemplify the integration of sensors and scales at a super-site located in the province of Cáceres, which aims to serve as a reference for the implementation of similar observatories in other open forests at the national, European, and global levels. Biophysical and spectral data on trees with and without visual decay symptoms (defoliation) have been collected and compared in order to determine the biophysical variables at the leaf level that are related to these symptoms and whether this translates into spectral differences at the canopy level that can be detectable by very high spatial resolution satellites such as Pléiades Neo.

2. MATERIAL AND METHODS

2.1. Study site

The main study site (super-site) for the SensOFOREST project is the Majadas de Tiétar experimental station (39°56'25" N, 5°46'28'' W), which belongs to the ICOS-Ecosystem and ICP Forest networks. It is a typical Spanish *dehesa* with average annual temperature of 16.6 °C and average annual precipitation of 600 mm. It has around 20% tree cover, a density of 25 trees/ha, and an average diameter at breast height (DBH) of 46 cm, making it fully representative of open, evergreen sclerophyllous forests of *Quercus Ilex* L. in southern Europe.

2.2. Multi-scale biophysical and spectral data

In this study, we focus on the analysis of data acquired in two experimental campaigns carried out at the Majadas de Tiétar super-site on September 17 2024 and July 3 2025. During these campaigns, samples were taken and biophysical and spectral variables were measured both at the leaf and canopy levels. All measurements were taken on 12 trees selected in two sampling areas (Fig. 1). Six target trees were identified in each area, three of which had visual decay symptoms in the form of low to moderate defoliation (20 to 60 %) (Fig. 1).

Figure 1. Sampling areas at the Majadas de Tiétar experimental station as observed from the Pléiades Neo sensor on July 3 2025. Trees without symptoms (< 20 % defoliation) are marked in green and those with symptoms of decline (20-60 % defoliation) are marked in yellow in both areas.

In accordance with ICP-Forest guidelines (http://icp-forests.net/), leaves were collected from the upper third of the canopy for foliar sampling. In these open forests, trees show maximum differences in nutrient content, leaf area, water, and pigments between the south and north orientations of the crowns. Therefore, branches from the upper third of both orientations were sampled. Two types of samples were taken, one at midday including 12 leaves (six from the north and six from the south orientations) on which chlorophyll a and b (Cab) and carotenoids (Cxc) concentrations per unit of leaf area were analyzed by spectrophotometric methods. The second sample, consisting of 100 leaves, was used to estimate the average leaf area (ALA), specific leaf area (SLA), equivalent water thickness (EWT), and nutrients (N and Mg) per unit of leaf area. Additionally, leaf area index (LAI) of the 12 individual trees was measured using a LAI2200-C Plant Canopy Analyzer averaging 4 measurements per tree taken under homogeneous diffuse illumination conditions (at sunset).

During the campaigns, image acquisition was programmed and obtained from the Pléiades Neo satellite. This satellite belongs to an optical constellation of commercial satellites with very high spatial resolution operated by Airbus Defence and Space. Pléiades Neo obtains information in seven spectral bands: Panchromatic: 450-800 nm, Deep Blue: 400-450 nm, Blue: 450-520 nm, Green: 530-590 nm, Red: 620-690 nm, Red Edge: 700-750 nm and Near-infrared: 770–880 nm with a spatial resolution of 30 cm in panchromatic mode and 1.2 m in multispectral mode. In this study, only the multispectral mode bands were used. The images were acquired over the study area around 11:30 UTC. Six vegetation indices (VIs) proposed in the literature for monitoring vegetation status were calculated from the multispectral bands (Table 1). Spectral information from bands and VIs was extracted from the target trees selecting pixels from the crown center and discarding the most peripheral areas to avoid contamination from the senesced grass background and the tree's own shadow projected onto the ground.

Table 1. Vegetation indices calculated from the multispectral bands of the Pléiades Neo image for the pixels selected in the crowns of the sampled trees.

Indices	Formula	Reference
NDVI	(NIR – RED) / (NIR + RED)	Rouse *et al*. 1974
NIRV	(NDVI-0.08)*NIR	Badgley *et al*. 2017
EVI	2.5 * ((NIR – RED) / ((NIR) + (6 * RED) – (7.5 * BLUE) + 1))	Huete *et al*. 1997
OSAVI	(NIR – RED) / (NIR + RED + 0.16)	Rondeaux *et al*. 1996
ReCI	(NIR / Red Edge) – 1	Gitelson *et al* 2003
GNDVI	(NIR – GREEN) / (NIR + GREEN)	Gitelson *et al*. 1996

The biophysical data obtained at the leaf and canopy level and the spectral data derived from the satellite images at the canopy level, were analyzed to determine whether there were significant differences between groups of trees with and without decay symptoms. First, a nonparametric Kruskal-Wallis Test was applied to all biophysical and spectral variables for the two sampling dates. Furthermore, correlations were calculated between the bands, IVs and the biophysical variables that showed significant differences between the two groups of trees, in order to determine the ability of Pléiades Neo images to estimate differences observed at ground level.

3. RESULTS

The Kruskal-Wallis Test applied to the biophysical data only showed significant differences (significance level > 95%) between the groups of trees with and without visual decline symptoms for the variables Cab and LAI (Table 2). As expected, trees with decay symptoms showed lower LAI values associated with the defoliation process. The LAI differences observed between symptomatic and asymptomatic trees were most evident in the September 2024 sampling campaign, likely due to the effect of phenology. Due to logistic constraints, the 2024 LAI measurements could not be taken simultaneously with the leaf sampling but were instead conducted a few months later, in January–February 2025, when holm oaks typically exhibit the lowest LAI values of the year. This would also explain why LAI values are higher in 2025 even in symptomatic trees. Surprisingly, Cab values measured at the leaf level were generally higher in symptomatic trees (Fig.2) which may be related to a compensatory response to defoliation.

In the case of the Pléiades Neo spectral data, individual bands did not show significant differences (Table 2) but three IVs did. Two of them are typically more related with vegetation structure (NDVI and MSR) and the third one is usually applied to the estimation of pigments (ReCI).

Table 2. Results of the nonparametric Kruskal-Wallis Test to analyze difference between trees with and without visual decay symptoms applied to biophysical and spectral variables obtained in the September 2024 and July 2025 experimental campaigns (n=24). The asymptotic significance (Sig.) is shown.

Biophysical	Sig.	Spectral (Pléiades Neo)	Sig.
ALA	0.326	B1	0.298
SLA	0.817	B2	0.488
EWT	0.453	B3	0.751
LAI	**0.001**	B4	0.402
Cab	**0.043**	B5	0.862
Cxc	0.149	B6	0.817
N	0.525	NDVI	**0.04**
Mg	0.817	NIRV	0.248
		EVI	0.453
		OSAVI	0.133
		ReCI	**0.05**
		GNDVI	0.184

Regarding the correlation between biophysical and spectral variables, we found similar moderated but significant (significance level > 95%) positive correlations between the VIs NDVI, MSR and ReCI derived from the Pléiades images and the Cab measured at the leaf level (Pearson ~0.45). The correlations were similar (Person 0.43 to 0.46) with the three IVs and LAI. However, in this case, the sign of the correlation was negative. This is contrary to expectations and confirms the inverse relationship found between the tree LAI and the Cab measured at the leaf level in the sampled trees.

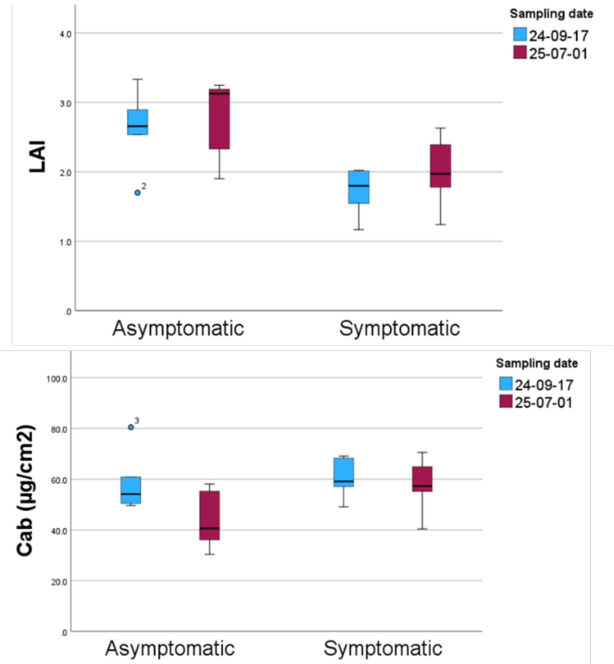

Figure 2. Box plots of leaf area index (LAI) and Cab measured in the experimental campaigns (September 2024 and July 2025) on selected trees with and without visual decay symptoms.

The preliminary results obtained in the two experimental campaigns reveal that it is possible to estimate some critical variables related to forest health conditions (pigment content and defoliation) using very high spatial resolution satellite images such as Pléiades Neo. However, the spectral indices analyzed were not exclusively related to the differences observed in specific foliar parameters such as Cab but inversely related to canopy level structural variables such as LAI. The differences detected in water content between trees with and without symptoms were not detectable at the canopy level with this type of imagery. This can be related with the spectral resolution of Pléiades Neo images, with broad bands that do not cover the shortwave infrared region which makes it difficult to observe absorption features of water and other components such as proteins, lignin and cellulose that could reveal stress conditions and are detectable in this spectral region (Buitrago et al., 2018). Future studies will analyze these open questions through the multi-scale integration of the SensOFOREST project dataset, including leaf level spectroscopy and hyperspectral drone imagery. This information could help disentangle the contribution of biochemical components at the leaf level from structural components in order to understand the contribution of each to the spectral response.

4. ACKNOWLEDGEMENTS

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