MONITORING FOREST HEALTH WITH SUN-INDUCED CHLOROPHYLL FLUORESCENCE OBSERVATIONS AND 3-D RADIATIVE TRANSFER MODELING

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ABSTRACT

This study present in situ measurements and model simulations aimed to understand the ability of sun-induced fluorescence (SIF) and other physiological and structural hyperspectral indices as an early indicator of forest decline. Experiments were conducted over an oak forest (*Quercus ilex*) affected by water stress and *Phytophthora* infection in the southwest of Spain. The robustness of the SIF quantification through the Fraunhofer Line Depth (FLD) principle with three spectral bands F (FLD3) was assessed using high-resolution hyperspectral imagery. FluorFLIGHT, a modified version of the 3-D radiative transfer model FLIGHT was developed to enable the simulation of canopy radiance and reflectance including fluorescence effects accounting for forest structure. Fluorescence retrievals performed better than structural and physiological indices. Albeit other pigment-related vegetation indices such as CRI550515 and RNIRCRI700 were also strongly related to physiological variables. The 3D modelling approach significantly improved the relationship between Fs and SIF and enabled the quantification of SIF as a function of fractional cover, leaf area index and chlorophyll content, yielding significant relationships between Fs ground-data measurements and fluorescence quantum yield estimated with FluorFLIGHT. The methodology also demonstrated its capabilities for mapping SIF at the crown level to detect early damage assessment in oaks undergoing forest decline.

Index Terms— Fluorescence, hyperspectral indices stress detection, hyperspectral, SIF, RTM, forest dieback, oak forest, *Phytophthora* infection

1. INTRODUCTION

A variety of environmental stresses such as drought, temperature, oxygen deficiency, water stress or salinity causes a depression of photosynthesis and efficiency of photosystem II in plants [1]. These effects are not easily reversible even in resistant species such as Mediterranean oaks [2]. Sun-induced fluorescence (SIF) has been proven to serve as a proxy for photosynthesis activity and therefore, as an early indicator of physiological alterations for global monitoring of vegetation. A large number of narrow spectral band vegetation indices has been proposed to assess plant physiology from remote sensing. Most of the studies are focused on demonstrating the sensitivity of VI to different biophysical variables such as canopy structure and photosynthetic pigments, including chlorophyll, xanthophylls and carotenoids in different vegetation canopies [3].

Despite the fact of several studies already focused on testing these indicators on crop and homogeneous canopies, a little effort has been made for forest and heterogeneous canopies. For this reason, there is a growing need for a better understanding of how forest structure effects SIF and other VI, and the applicability of these physiological indicators of forest health condition. Here we present new field experiments and model simulations aimed to understand the ability of SIF and other physiological and structural hyperspectral indices as an early indicator of forest decline.

2. MATERIAL AND METHODS

2.1. Data collection

In situ measurements were collected in an oak forest (*Quercus ilex*) located in the southwest of Spain where water stress and *Phytophthora* infection has been previously described [4]. Field measurements were made on three consecutive days (25-28 August in 2012) and concurrently with acquisition of airborne imagery (12:00 to 13:00 h local time) over the experimental field. The field data measurements were conducted in 15 oak trees (*Quercus ilex* subsp. Bellota) collecting different physiological indicators such us water potential (wp), de-epoxidation state of xanthophyll (DEPS) and steady-state leaf fluorescence (Fs). Wp was measured with a pressure chamber (SKPM 1400, Skye Instruments Ltd, Powys, UK) (Scholander et al., 1965) from 12 branches per tree, three branches per orientation in the four cardinal directions. Fs was measured on five leaves per orientation and tree, with a total of 300 leaves sampled

using a FluorPen FP100 (Photon Systems Instruments, Brno, Czech Republic), which was self-calibrated at the start of each session. Lastly, leaf pigments were measured as described in [5] from a total of 48 leaves per tree, 12 samples per orientation, with a total of 720 leaves sampled. The DEPS was calculated as (A+Z)/(A+V+Z) [6], where V is violaxanthin, A is antheraxanthin and Z is zeaxanthin.
The images were collected with a visible and near-infrared (VNIR) micro-hyperspectral imager (Micro-Hyperspec VNIR model, Headwall Photonics, MA, USA). Flight details and sensor configuration can be found in [3].

2.2. Data analysis

For this study, we calculated several spectral indices related to different biophysical parameters: i) tree crown structure, caused by the sensitivity of the near-infrared bands to the foliar scattering of the canopy NDVI, SR, the normalized family of indices OSAVI, MSAVI, LIC among other indices; ii) pigment related indices VOG, GM, TCARI, TCARI-OSAVI, CI, TVI, SRPI, NPQI, NPCI, CTR1, CAR, Datt, SIPI, CRI550, CRI550515, RNIRCRI55, RNIRCRI70; iii) epoxidation state of the xanthophyll cycle caused the absorption of three carotenoid pigments that are active in the xanthophyll cycle: violaxanthin (V), antheraxanthin (A), and zeaxanthin (Z) (family of PRI and modified PRI indices); and iv) chlorophyll fluorescence emission by photosystems I (PS-I) and II (PS-II) (CUR index). A detailed description of this selection of vegetation indices and their formulation can be found in [3], [7], [8] and [9], [10].

The robustness of the SIF quantification through the Fraunhofer Line Depth (FLD) principle with three spectral bands F (FLD3) was assessed using high-resolution (60 cm) hyperspectral imagery extracting sunlit crowns, pure tree crowns and aggregated pixels. SIF accuracy retrievals using the FLD approach with similar instruments with wider spectral bandwidths (3-6.5 nm FWHM) has been reviewed using modelling and experimental data by different authors ([3], [8], [10]–[13]).

The potential of using FluorFLIGHT to predict SIF from hyperspectral images in a heterogeneous oak forest was also analyzed. For this purpose, FluorFLIGHT was used in a multi-step Look-Up Table (LUT) based inversion scheme described in [11], to retrieve pure-crown SIF from a complex scene accounting for the influence of scene structure and composition. A synthetic dataset of 1000 FluorFLIGHT simulations was generated for a set of leaf fluorescence quantum efficiency (Fi) values and forest structure scenarios. The inputs parameters used to generate the simulations were defined based on field measurements and hyperspectral imagery, mimicking the architecture and level of affectation of the study area. The simulated spectra with FluorFLIGHT were used here to retrieve SIF using the inverted values of FC, LAI and Ca + b as constraints in a regularization strategy attending to reduce the influence of structural canopy variables of the fluorescence signal. The inverted values of crown FLD3 and leaf Fi were obtained by matching measured and modelled LUT spectra and finding the optimal values. Finally, model-based retrievals derived from hyperspectral imagery were used for mapping the fluorescence quantum efficiency within the oak forest.

3. RESULTS

Comparing the FLD3 performance to all the others VI tested (Fig.1), FLD3 showed the strongest relationship with the physiological variables yielding a significant correlation coefficient for wp ($r = 0.75$; $p < 0.01$), DEPS ($r = -0.79$; $p < 0.001$) and Fs ($r = 0.85$; $p < 0.001$). Therefore, this result demonstrates that the FLD3 is compatible with the retrieval of the most sensitive plant traits linked with the disease.
Other pigment related vegetation indices such as SRPI, NPQI, NPCI, CTR1, Datt, SIPI, CRI_{550}, CRI_{550515}, $RNIRCRI_{550}$ and $RNIRCRI_{700}$ were also strongly related to the physiological variables measured at the leaf level. In particular, the strongest relationship found for this group of vegetation indices was between CRI_{550515} and wp ($r = -0.59$; $p < 0.01$), DEPS ($r = 0.48$; n.s) and Fs ($r = -0.65$; $p < 0.01$) and between $RNIRCRI_{700}$ and wp ($r = -0.66$; $p < 0.01$), DEPS ($r = 0.40$; n.s) and Fs ($r = -0.69$; $p < 0.01$). Whereas the same relationship was weaker for most of the PRI and modified PRI indices, with the highest correlations found between PRICl and wp ($r = -0.33$; n.s), DEPS ($r = -0.43$; n.s) and Fs ($r = 0.49$; n.s). Poor relationships were also obtained with most of the structure related vegetation indices tested with correlation coefficients lower than ($r^2=0.25$, n.s).

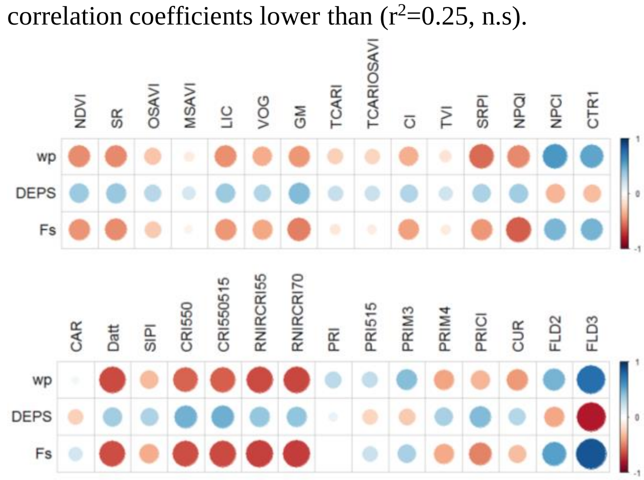

Figure 1. Correlation analysis obtained for the relationship between water potential (wp), de-epoxidation state of xanthophyll (DEPS) and leaf steady-state fluorescence (Fs) and all vegetation indices selected for this study.

Our study shows that the observed *Phytophthora*-induced leaf physiological changes are consistently linked with alterations of plant functional traits detected remotely. In particular, FLD3 revealed statistically significant and consistent relationship with canopy physiology and therefore, a significant utility for precision physiological condition characterisation. Although with lower statistical significance than FLD3, the VI CRI_{550515} or $RNIRCRI_{700}$ showed a consistent relationship with the physiological variables. Operationally, the spectral band sets required to calculate those VI are more feasible than the FLD, which requires very narrow spectral bands (lower than 5nm) and a high signal-to-noise ratio. To what extent the use of VI is more feasible or less than FLD depends on the accuracy required for monitoring *Phytophthora* infections. The natural variability in the physiological condition of oaks affected by *Phytophthora* will condition the actual accuracy needed for the detection of *Phytophthora* infection over time.

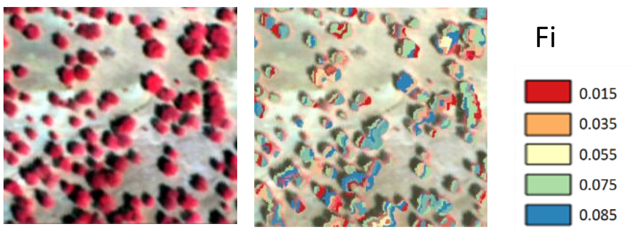

Figure 2. Fluorescence quantum efficiency (Fi) retrieval at the crown level estimated with FluorFLIGHT (right) and the 60-cm hyperspectral image using the fluorescence in-filling method F (FLD3) within the oak forest (left).

The robustness of the SIF quantification through the Fraunhofer Line Depth (FLD) principle with three spectral bands F (FLD3) was further assessed using high resolution (60 cm) hyperspectral imagery extracting sunlit crowns. Results showed the link between SIF (FLD3) extracted from sunlit crown pixels and the tree physiological condition in the context of disease infection, yielding significant relationships (r^2=0.57, p<0.01) for wp, (r2=0.63, p<0.01) for DEPS, and (r^2=0.74, p<0.01) for Fs. Fluorescence signal retrieval using the 3D modelling approach was then applied for mapping fluorescence emission as an early spatial detector of *Phytophthora* infections (Fig. 2).

4. CONCLUSIONS

Measuring sun-induced fluorescence and physiological vegetation indices remotely is a valuable tool to track the health and productivity of forest but also brings important challenges. This study demonstrates a link between physiologically-based narrow-band vegetation indices and SIF retrieved from hyperspectral images and the physiological health condition of oak trees. Model inversion SIF estimates using the 3-D FluorFLIGH model enabled the detection and evaluation of root pathogen infections and water stress of oak trees. Local patchiness in disease presence/severity can be observed with the high local variability of the SIF inversion map estimated at the oak site.

5. ACKNOWLEDGEMENTS

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