Leaf Biochemistry Estimation on EU High-Value Crops with ROSIS and DAIS Hyperspectral Data and Radiative Transfer Simulation

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ABSTRACT

This manuscript provides a description of progress made on the investigation of estimation of leaf biochemistry on high-value crops using hyperspectral remote sensing imagery. Hyperspectral optical indices related to leaf chlorophyll content were used to test different assumptions under open and row-crop canopies, specifically *Olea europaea* L. (olive trees) and *Vitis vinifera* L. (vineyards). *Scaling-up* methods were tested as a function of the different spatial resolutions of ROSIS and DAIS datasets acquired over two olive groves and ten vineyard fields in southern and northern Spain, respectively, during the HySens 2002 campaign. Leaf-level biochemical estimation from 1-m ROSIS and 5-m DAIS data required different modeling assumptions, enabling in some cases the use of PROSPECT-SAILH radiative transfer simulation when targeting olive-tree crowns. At lower spatial resolutions the soil and shadow scene components were considered through the linked PROSPECT-SAILH-FLIM models. These considerations along with the calculation of predictive equations using MCARI/OSAVI to minimize soil background variations in these canopies are also discussed.

Keywords: chlorophyll content, olive tree, vineyard, hyperspectral, remote sensing, radiative transfer, FLIM.

1 INTRODUCTION

The European Union maintains a world leading position on two high-value crops, olive trees (*Olea europaea* L.) and vineyards (*Vitis vinifera* L.). It represents the largest olive oil producer in the world and widespread production throughout the Mediterranean region, with 50% of the area in Spain and 25% in Italy. The EU wine market accounts for 45% of wine-growing areas, world leader in terms of area, production and consumption. Research conducted under the European Union HySens-2002 funded project aimed to investigate physical methods with ROSIS and DAIS 7915 high-spatial hyperspectral remote sensing imagery to estimate leaf biochemical constituents in olive groves and vineyard canopies. Leaf chlorophyll $a+b$ (C_{a+b}) and leaf area index (LAI) are indicators of stress and growth that may be estimated by radiative transfer modelling from hyperspectral data in the 400-2500 nm spectral region. Differences in remote sensing reflectance between healthy and stressed vegetation due to changes in C_{a+b} levels have previously been detected in the green peak and along the red edge spectral region (e.g. Rock *et al.*, 1988; Vogelmann *et al.*, 1993; Carter, 1994), thereby suggesting the feasibility of remote detection of crop stress.

Estimation of such leaf biochemical and canopy biophysical variables from remote sensing data requires appropriate modelling strategies for *Olea europaea* L. and *Vitis vinifera* L. canopies, accounting for structure through its dominant effect on the bi-directional reflectance (BRDF) signature. Little such work has been reported in which the radiation interception by olive canopies have been modeled using radiative transfer methods and compared to hyperspectral remote sensing data. Research that deals with modelling the radiation interception by olive canopies has begun to emerge with the work by Mariscal *et al.* (2000) to develop a RT model for PAR estimation, and Villalobos *et al.* (1995) for LAI estimation. Successful estimation of leaf biochemistry from remote sensing methods in open canopies of *Olea europaea* L. and *Vitis vinifera* L. has remained an elusive goal to date, presumably due to the difficulties to access data from hyperspectral sensors and to the complexity of the physical approaches required for modeling such canopies. C_{a+b} and other leaf biochemical constituents such as dry matter content (C_m) and water content (C_w) are indicators of plant stress and nutritional deficiencies caused by elements N, P, K, Fe, Ca, Mn, Zn and Mg, among others (Marschner *et al.*, 1986; Fernández-Escobar *et al*., 1999; Jolley and Brown, 1994; Chen and Barak, 1982; Wallace, 1991; Tagliavini and Rombolà, 2001). Chlorosis in olive trees caused by such deficiencies can be successfully treated thereby improving yields and the final quality of the fruit (Chova et al, 2000; Cordeiro *et al.*, 1995; Fernandez-Escobar *et al.*, 1993; Gutiérrez-Rosales *et al.*, 1992). Moreover, Fe and N deficiencies resulting in chlorosis symptoms in vineyards cause a decrease of fruit yield and quality in the current and the subsequent year as fruit buds develop poorly (Tagliavini and Rombolá, 2001). Fertilization of crops affects carbon storage, generates vegetation injury with prolonged N additions (Schultze *et al.*, 1989) and increases N losses by gaseous and solute pathways to the soil. Competing goals in agriculture are supplying adequate N while minimizing N losses (Daughtry *et al.*, 2000).

Several narrow-band leaf-level optical indices might be utilized in hyperspectral canopy reflectance data for C_{a+b} estimation (Zarco-Tejada *et al.*, 2001). *Red Edge Reflectance Indices* such as Vogelmann (R_{740}/R_{720}), (R_{734}-R_{747})/(R_{715}+R_{726}); Gitelson & Merzylak (R_{750}/R_{700}); Carter (R_{695}/R_{760}); Zarco-Tejada & Miller (R_{750}/R_{710}), and *Spectral and Derivative Indices* such as the red edge parameters λ_p, λ_o, σ (Miller *et al*. 1990), and derivative ratios (D_{715}/D_{705}); DPR1 ($D_{\lambda p}/D_{\lambda p+12}$), and DP21 ($D_{\lambda p}/D_{703}$) have been demonstrated to yield the best results for C_{a+b} estimation from canopy-level reflectance using airborne hyperspectral data (Zarco-Tejada *et al.,* 2001) in closed forest canopies. Recently, combinations of indices based on TCARI, MCARI, and OSAVI, such as TCARI/OSAVI and MCARI/OSAVI (Haboudane *et al*., 2002) have been demonstrated to successfully minimize soil background variation and LAI canopy changes, providing predictive relationships readily used for precision agriculture applications with CASI hyperspectral imagery.

The application of such optical indices in discontinuous crop canopies such as *Olea europaea* L. and *Vitis vinifera* L., where canopy structure plays an important role in the modelled reflectance, through the effect of LAI, shadows and soil, needs extensive research with airborne hyperspectral data of optimum spatial and spectral resolution. Vine row geometry leads to variation in shadow scene proportions as a function of sun azimuth and zenith angles relative to row orientation, affecting the vegetation index calculated and the estimated biochemical constituent. Olive trees are grown in regular patterns with tree spacing typically between 6 and 12 m, resulting in an important effect of soil reflectance and shadows on the canopy reflectance. Turbid-medium models such as SAILH (Verhoef, 1984) and FLIM (Rosema *et al.*, 1992) were linked to leaf PROSPECT model (Jacquemoud and Baret, 1990) and tested in both canopies under different scene component proportions.

2 AIRBORNE AND FIELD DATA COLLECTION

A total of 8 hyperspectral images were collected by the German Aerospace Center (DLR) with ROSIS and DAIS sensors under the HySens campaign in July 2002. Four DAIS and four ROSIS images were acquired at 5 and 1 m spatial resolution, respectively, from vineyards and olive fields located in Burgos/Palencia (northern Spain) and Córdoba/Seville (southern Spain), respectively (Figure 1). Imagery were processed to at-sensor radiance at DLR, and atmospheric correction performed with MODTRAN using aerosol optical depth at 550nm collected with a Micro-Tops II sunphotometer (Solar Light Co., Philadelphia, PA, USA) at the time of airborne acquisition. Soil reflectance spectra collected were used to perform a *flat-field* correction that compensated for residual effects of atmospheric water and oxygen absorption.

A field sampling campaign was conducted for biochemical analysis of leaf C_{a+b} in study areas of *Olea europaea* L. and *Vitis vinifera* L. Reflectance (ρ) and transmittance (τ) measurements of olive and vine leaves were carried with a Li-Cor 1800-12 Integrating Sphere (Li-Cor, Inc., Lincoln, NE, USA), coupled by a 200 μm diameter single mode fiber to an Ocean Optics model USB2000 spectrometer (Ocean Optics Inc., Dunedin, FL, USA), with a 1024 element detector array, 0.5 nm sampling interval, and ~7.3 nm spectral resolution in the 340-940 nm range. A leaf-level measurement protocol for leaf reflectance and transmittance was based on the method by Harron (2000), and a custom-made port was used for the olive leaf optical measurements (Figure 2a). LAI was measured using a Li-Cor PCA LAI-2000 instrument (Li-Cor, Inc., Lincoln, NE, USA) on vineyard study plots.

Two fields of olive groves in southern Spain were selected to secure a gradient in biochemical concentration, comprising groves of irrigated and non-irrigated crops. Differences in biochemical properties at the irrigated field were due to a random experimental study conducted with 4 fertirrigation treatments, with 6 blocks per treatment, and 4 trees per block. Treatments consisted on drip irrigation with water and no fertilizer, and 200, 400 and 600 g N per tree / irrigation with NPK fertilization 4:1:3 (Figure 2b). A total of 46 trees were sampled for biochemical constituents from the irrigated and non-irrigated fields. Additional field measurements made at the sites consisted on soil reflectance, shadow reflectance, and crown transmittance using a diffuse cosine receptor under the trees and under direct sun. The 13 study sites of *Vitis vinifera* L. were selected from a plot network that also comprised random experimental design with nitrogen treatments, therefore generating a gradient in the leaf biochemistry sought for this study.

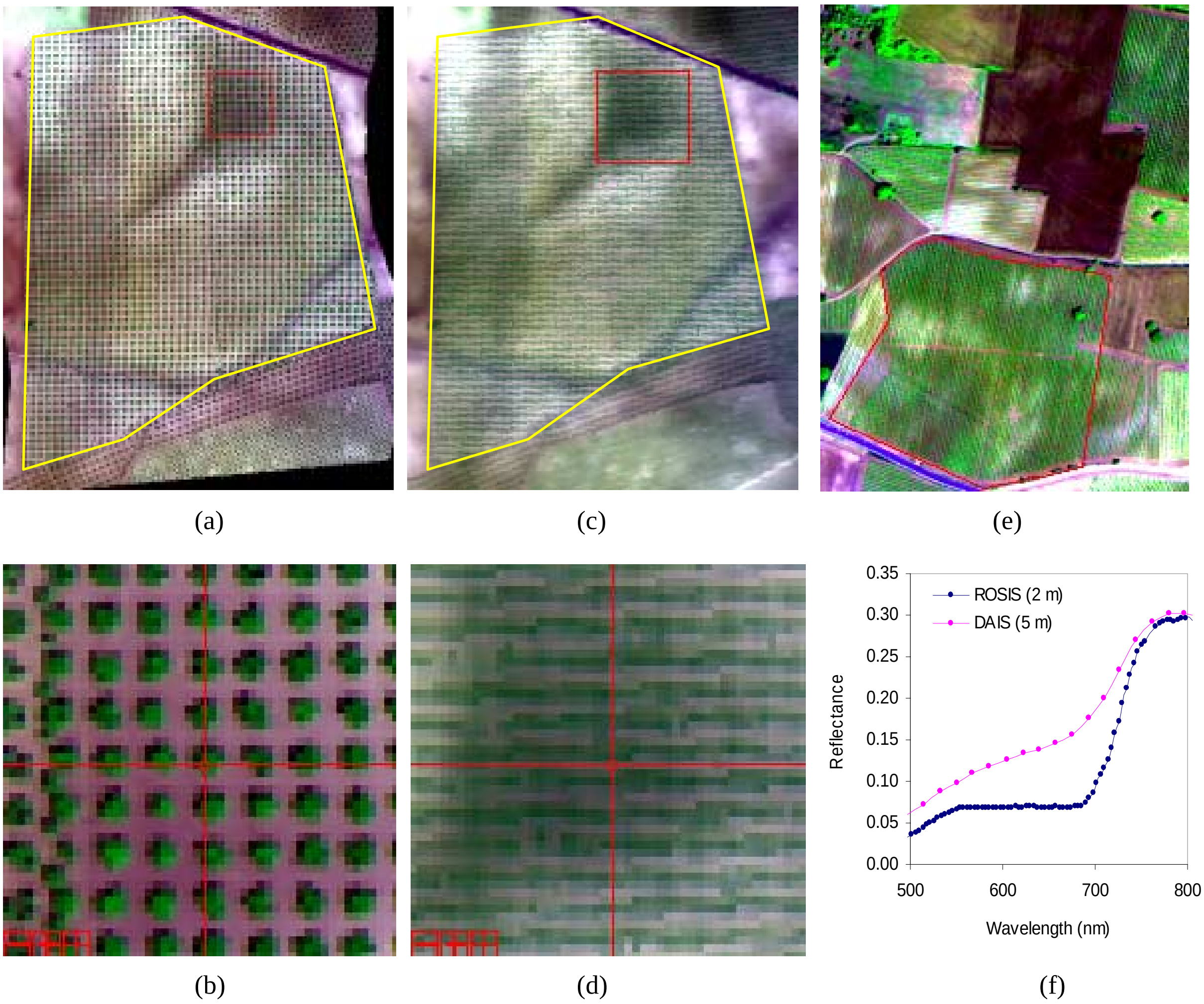
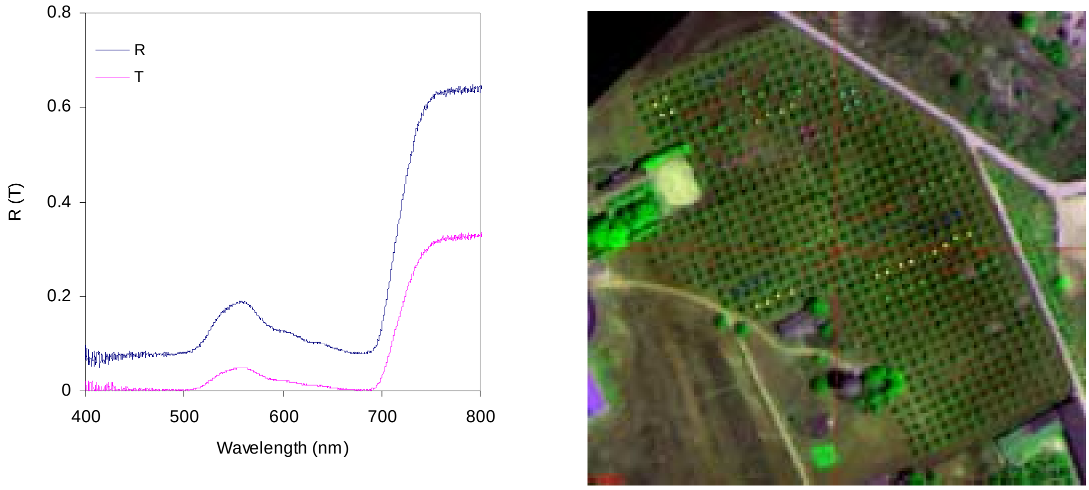


Figure 1. ROSIS (a,b,e) and DAIS (c,d) imagery collected at 1m and 5m spatial resolution respectively from one of the study fields of *Olea europaea* L. in Córdoba (Spain) (a to d) and a vineyard field (e). Plot (f) shows the effect of scene components as function of the pixel size for ROSIS (targeting crown, (b)) and DAIS imagery (with crowns, shadow and soil components, (d)).

3 METHODS

Hyperspectral reflectance spectra from ROSIS and DAIS at 1 and 5 m spatial resolution, respectively, were extracted from olive and vineyard canopies at the study sites. Spectra were extracted from the imagery for each tree where field sampling was conducted, targeting crowns with ROSIS imagery. At the vineyard study sites, with no possibility to target pure vegetation pixels, two sets of spectra were extracted from the of 8x8 m plots, i) selecting all pixels; and ii) targeting the brightest pixels in the NIR, therefore minimizing the effects due to soil and shadows.

Radiative transfer modeling methods employed consisted of coupling the PROSPECT model for leaf-level simulation, with SAILH model when targeting olive tree crowns (PROSPECT-SAILH) with the ROSIS data. With lower spatial resolution, therefore with pixels aggregated from soil, shadow and crown components, the modeling method consisted on linking SAILH and FLIM models (PROSPECT-SAILH-FLIM). Assessment of such a coupling method using PROSPECT-SAILH-FLIM for open olive grove canopies was conducted for their ability to estimate leaf C_{a+b} by scaling up of hyperspectral optical indices such as R_{750}/R_{710}, MCARI, TCARI, OSAVI, and combined indices such as TCARI/OSAVI and MCARI/OSAVI as in Haboudane *et al.* (2002). The SAILH model simulated the crown reflectance, and FLIM simulated the geometry of the open canopy, including the effects of vegetation crowns, sunlit and shadowed background soil. A sensitivity study was conducted to simulate the effects of leaf C_{a+b} and canopy LAI on canopy reflectance, studying the effects of soil reflectance variation on the proposed TCARI/OSAVI and MCARI/OSAVI indices used for deriving predictive relationships. Input parameters for PROSPECT are the N parameter, chlorophyll content (C_{ab}), dry matter content (C_m) and water content (C_w). SAILH model required leaf reflectance (ρ) and transmittance (τ) (from PROSPECT), soil reflectance ρ_s from the ROSIS imagery, leaf angle distribution function (LADF) set to plagiophile in olive canopies, leaf area index (LAI), and model-estimated skylight irradiance (skyl). The FLIM model input variables were tree density (T_δ), crown diameter (C_d), crown height (C_h) and crown leaf area (C_{LAI}), crown extinction coefficient (C_α), sun angle (θ_s), background reflectance (ρ_s) and crown reflectance (ρ_c) from SAILH. Olive and vine leaf reflectance and transmittance measurements collected from the study sites were inverted with PROSPECT to derive the N parameter required for the *scaling-up* of combined optical indices, providing values of N~3 for olive leaves, and N~1.5 for vine leaves.



(a) (b)

Figure 2. Olive leaf reflectance and transmittance measurements collected with a Li-Cor 1800-12 Integrating Sphere coupled to an Ocean Optics model USB2000 spectrometer (a). Random experimental study conducted with 4 fertirrigation treatments, with 6 blocks per treatment, and 4 trees per block on the irrigated olive field in Seville (Spain) (b).

4 RESULTS

The index MCARI/OSAVI performed the best among the indices tested when targeting crowns (r^2=0.69), compared to TCARI/OSAVI (r^2=0.48) and R_{750}/R_{710} (r^2=0.07). For vineyard study sites, MCARI/OSAVI index obtained r^2=0.54 with C_{ab} measured in the study plots. Therefore, predictive relationships were calculated for MCARI/OSAVI index from PROSPECT-SAIH (Figure 3, top left and right) using a gradient of soil backgrounds found on the ROSIS imagery, with LAI=0.5. Soil background variation proved to have low effect on the predictive relationships developed with MCARI/OSAVI index (Figure 3, top right). Results of the C_{ab} estimation for targeted crowns with the prediction relationship based on MCARI/OSAVI and PROSPECT-SAILH gave r^2=0.67 and RMSE=10 $\mu g/cm^2$ (Figure 3, bottom left). Nevertheless, prediction relationships built on PROSPECT-SAILH for crowns were demonstrated to be inaccurate when applied to pixels aggregated with soil and shadow scene components (Figure 3, bottom right) yielding an r^2=0.29. In this case of aggregated scene components, a predictive relationship with MCARI/OSAVI was developed using PROSPECT-SAILH-FLIM, improving the estimation of C_{ab} to r^2=0.41 and RMSE=11 $\mu g/cm^2$ (Figure 3, bottom right).

5 CONCLUSIONS

This paper discusses different methods for stress detection through chlorophyll content estimation in heterogeneous crop canopies, such as olive groves and vineyard fields. Modeling methods were used which demonstrated the need for accounting for scene components in these open and row-crop canopies, such as soil background and shadows. When targeting crowns using 1m spatial resolution ROSIS data, PROSPECT-SAILH simulation obtained good results when building predictive relationships using the MCARI/OSAVI optical index. The index MCARI/OSAVI was shown to be insignificantly affected by soil background changes, while other indices that performed well in closed canopies, such as R_{750}/R_{710}, did not work in open canopies where soil background plays an important role. When pixels are comprised of a mixture of different scene components, such as vegetation reflectance, soil background and shadows, the need for a model to account for those effects is demonstrated. The simulation with PROSPECT-SAILH-FLIM was shown to work well in open canopies such as olive groves, where soil background and shadows become important.

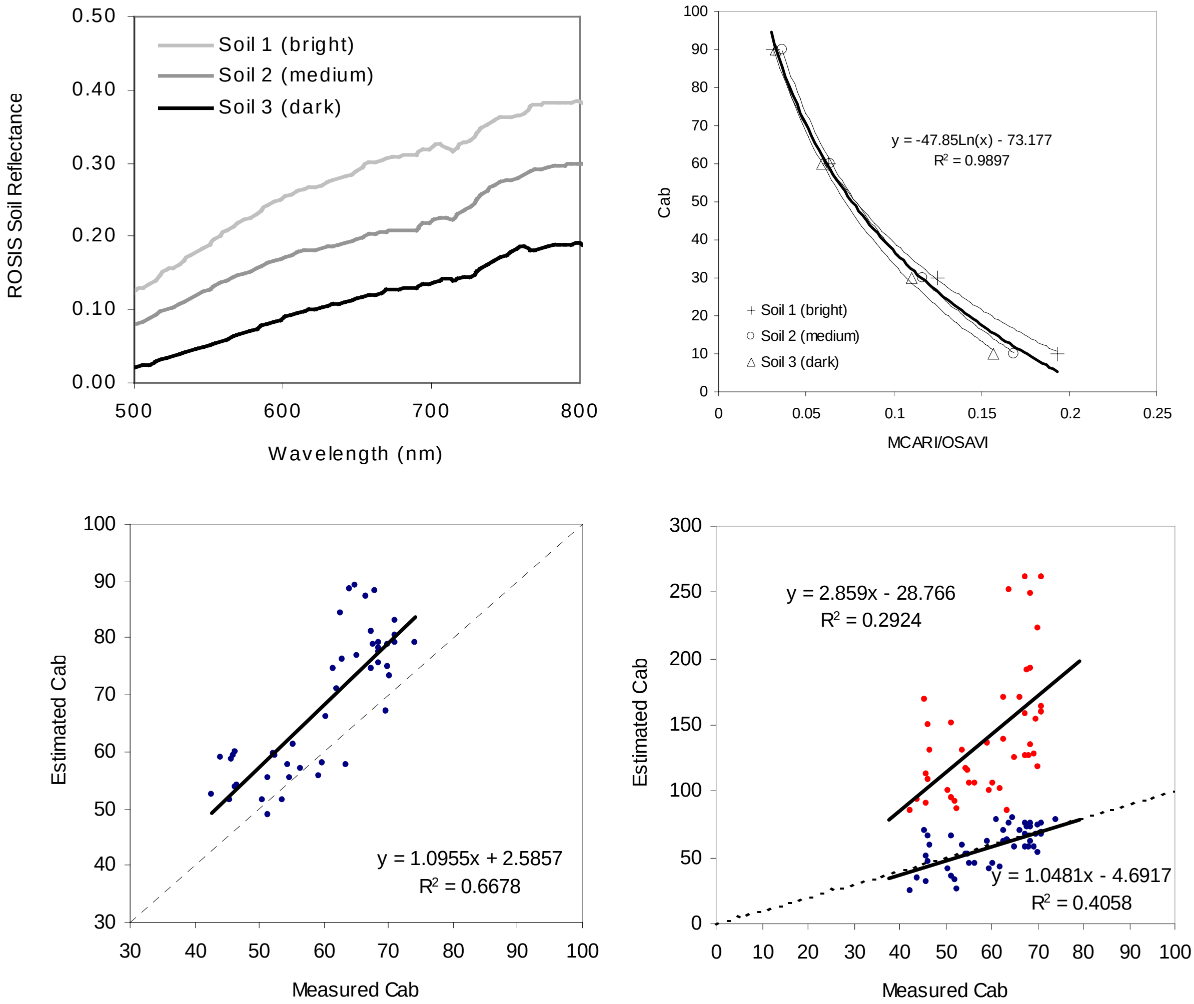


Figure 3. Extreme soil spectra obtained from ROSIS across the study sites of olive fields (top left) used for calculating the predictive relationship between MCARI/OSAVI and C_{ab} concentration (top right). Bottom left shows the estimations of C_{ab} when applying MCARI/OSAVI predicting relationship to ROSIS crown reflectance spectra with PROSPECT-SAILH. Bottom right plot shows the crown predictive relationship applied to aggregated pixels through PROSPECT-SAILH (red) and improving the estimation when using PROSPECT-SAILH-FLIM (blue).

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