-Preprint version-
Paper submitted to the International Journal of Applied Earth Observation and Geoinformation

Hyperspectral and multispectral satellite sensors for mapping chlorophyll content in a Mediterranean *Pinus sylvestris* L. plantation

Rafael Mª Navarro-Cerrillo[a,*], Jesus Trujillo[a], Manuel Sánchez de la Orden[b], Rocío Hernández-Clemente[a]

[a] Department of Forestry Engineering, University of Cordoba, Edf. Leonardo da Vinci, Campus de Rabanales, 14075 Cordoba, Spain
[b] Department of Geomatics, University of Cordoba, Edf. C-5, Campus de Rabanales, 14075 Cordoba, Spain

A B S T R A C T

A new generation of narrow-band hyperspectral remote sensing data offers an alternative to broad-band multispectral data for the estimation of vegetation chlorophyll content. This paper examines the potential of some of these sensors comparing red-edge and simple ratio indices to develop a rapid and cost-effective system for monitoring Mediterranean pine plantations in Spain. Chlorophyll content retrieval was analyzed with the red-edge R_{750}/R_{710} index and the simple ratio R_{800}/R_{560} index using the PROSPECT-5 leaf model and the Discrete Anisotropic Radiative Transfer (DART) and experimental approach. Five sensors were used: AHS, CHRIS/Proba, Hyperion, Landsat and QuickBird. The model simulation results obtained with synthetic spectra demonstrated the feasibility of estimating $Ca+b$ content in conifers using the simple ratio R_{800}/R_{560} index formulated with different full widths at half maximum (FWHM) at the leaf level. This index yielded a $r^2 = 0.69$ for a FWHM of 30 nm and $r^2 = 0.55$ for a FWHM of 70 nm. Experimental results compared the regression coefficients obtained with various multispectral and hyperspectral images with different spatial resolutions at the stand level. The strongest relationships where obtained using high-resolution hyperspectral images acquired with the AHS sensor ($r^2 = 0.65$) while coarser spatial and spectral resolution images yielded a lower root mean square error (QuickBird $r^2 = 0.42$; Landsat $r^2 = 0.48$; Hyperion $r^2 = 0.56$; CHRIS/Proba $r^2 = 0.57$). This study shows the need to estimate chlorophyll content in forest plantations at the stand level with high spatial and spectral resolution sensors. Nevertheless, these results also show the accuracy obtained with medium-resolution sensors when monitoring physiological processes. Generating biochemical maps at the stand level could play a critical rule in the early detection of forest decline processes enabling their use in precision forestry.

Keywords:Multi and hiper spectral sensors
Chlorophyll
Mediterranean pine forests
Spectral vegetation indices

1. Introduction

Although forest ecosystems are characterized by the spatial variability of growth conditions and vegetation responses, it is common practice to manage them as homogeneous units (Schütz, 1997). Traditionally, broad-scale forestry has been based on features such as vegetation types or geoclimatic data rather than changes in vegetation condition. However, forest biophysical data retrieval is required for forest managers to make appropriate economic and environmental management decisions (Warning and Running, 2007).

Approaches commonly used to determine biophysical data include continuous fieldwork to map structural parameters (diameter, height, and growth) and physiological parameters (Leaf area index-LAI and chlorophyll content) by intensive sampling. These measurements are expensive and time-consuming and their results are sometimes difficult to spatially extrapolate. Alternative approaches based on use of remote sensing technologies to reduce the cost and time of data collection have been undertaken in various countries in the past decade (Tomppo et al., 2008).

Remote sensing has been recognized as a reliable method for estimating plant ecophysiological variables (Cohen et al., 2003; Hernández-Clemente et al., 2012). Among ecophysiological variables, LAI and chlorophyll content are widely used as indicators to study forest canopy status and physiological changes (Mohammed et al., 2000). Chlorophyll content ($Ca+b$) is a key biophysical variable that controls many biological processes such as photosynthesis, transpiration, and energy balance of terrestrial ecosystems (Blackburn, 2007; Warning and Running, 2007). Because of this ecological relevance, chlorophyll content maps are increasingly used as input for modeling biogeochemical processes and for detecting stress to enable remedial action to be planned (Lichtenthaler, 1996; Zarco-Tejada et al., 2005). A number of studies have linked responses in leaf chlorophyll to physiological stress (Carter and

Knapp, 2001). Changes in pigment content related to differences in reflectance between healthy and stressed vegetation have been detected in *green peak* and *red-edge* reflectance (e.g. Carter, 1994; Gitelson et al., 2003; Blackburn, 2007).

The most studied part of the vegetation spectrum is the spectral *red-edge* region, situated between 670 and 800 nanometers (nm) (Ustin et al., 2009). In forest ecosystems, red-edge indexes have been linked to decreasing chlorophyll, which is usually associated with stress events or senescence (Zarco-Tejada et al., 2001; Moorthy et al., 2008). Other chlorophyll-related broad-band vegetation indices (VIs) have been also used to better assess the effects of stress on vegetation vitality (Zarco-Tejada et al., 2004; Wu et al., 2009 Delalieux et al., 2009). Fairly strong but site-specific relationships between chlorophyll content and VIs have been found in various studies across different vegetation types (Gitelson et al., 2003; Moorthy et al., 2008; Main et al., 2011). The aim of using spectral indices or ratios is to minimize the effects of background interference, leaf surface interactions, and environmental interference (Peñuelas et al., 1995; Gitelson et al., 1996). Previous studies have considered the effects of chlorophyll content and leaf area index (LAI) in relationship to the reflectance at 550, 670, 700, and 801 nm bands. Moreover, several indices, including the ratios of NIR and red reflectance, NIR and green reflectance, red normalized difference vegetative index (NDVI), green NDVI, modified chlorophyll absorption in reflectance, soil-line vegetation index and optimized soil-line vegetation index in corn to estimate leaf chlorophyll content have been evaluated (Gitelson and Merzlyak, 1997; Daughtry et al., 2000; Main et al., 2011).

With few exceptions, such studies used broad-band multispectral data such as those obtained with Landsat TM/ETM+ (Gong et al., 2002). However, efforts in the remote sensing of canopy chlorophyll content via VIs have been hindered by the limitations in the spectral and spatial resolution of conventional broad-band sensors (Sims and Gamon, 2002; Moorthy et al., 2008). New sensors are capable of sub-meter resolution (e.g. Ikonos, QuickBird, and airborne sensors) and fine spectral resolution (e.g. hyperspectral sensors such as the Airborne Hyperspectral Scanner, Hyperion, and CHRIS/Proba). In recent years, a new generation of narrow-band multispectral satellite sensors has been designed to include off-chlorophyll absorption center wavebands (e.g. RapidEye, Worldview-2, and SumbandilaSAT); yet, conventional sensors will continue to be used to obtain biochemical maps of the canopy.

Radiative transfer (RT) models, including scaling-up and model inversion methods through coupling leaf and canopy transfer models, have been used to accurately detect changes in chlorophyll content in forest landscapes (Jacquemoud and Baret, 1990; Zarco-Tejada et al., 2004; Moorthy et al., 2008; Verrelst et al., 2010). RT models have the potential to increase the transferability of chlorophyll assessment methods to deal with variations in both leaf form and measurement methodologies and overcome the limitations of regressive empirical models. The PROSPECT model and a more complex approach such as the coupled PROSPECT + DART (Discrete Anisotropic Radiative Transfer) model have been used to predict chlorophyll content in heterogeneous coniferous forests (Demarez and Gastellu-Etchegorry, 2000; Malenovský et al., 2013).

However, there is a lack of studies on biochemical parameters of coniferous species in Mediterranean ecosystems. This is particularly true for pine plantations, which cover broad areas in Mediterranean countries (Deshayes et al., 2006). Given the great variety of air- and space-borne sensors that claim to be useful to map forest conditions, it is important to review the spatial and spectral resolution required for this purpose. Accordingly, the aim of this research was to compare chlorophyll content retrieval based on the red-edge R_{750}/R_{710} and simple ratio R_{800}/R_{560} indices using canopy modeling methods (PROSPECT-5/DART) and broad-band multispectral (Landsat TM, QuickBird) and narrow-band hyperspectral imagery (Hyperion, CHRIS/Proba, AHS) in forest sites dominated by Scots pine (*Pinus sylvestris* L.) in southern Spain. Chlorophyll content at the stand level was mapped as a tool to develop a rapid and cost-effective system to assess and monitor the condition of pine forests and to facilitate the prediction of forest health bioindicators.

2. Materials and methods

2.1. Study sites

The study area was located in southern Spain in the Penibetic mountain range, which has a broad range of geological and orographic features. The area is known as Sierra de los Filabres (37°22″ N, 2°50″ W, 150.000 ha between 300 and 2186 m.a.s.l) (Fig. 1). The climate is Mediterranean to semi-arid with low rainfall (mean annual precipitation 330 mm) and moderately mild temperatures (13.1 °C, 1000 m.a.s.l.) in the 1940–2007 period.

2.2. Sampling design and ground-based chlorophyll measurements

Nine plots of *P. sylvestris* L. were sampled (625 m^2); plot center locations were recorded with a real-time differential global positioning system (GNSS/GPS Systems, Leica). The error accepted for GPS measurements under the canopy was limited to an EPE (Estimated Position Error) <1 m. Plot locations in the forest are shown on the regional orthophoto image (Fig. 1). Forest structure was determined from a systematic inventory showing that forests are mainly dominated by *P. sylvestris*, with similar densities across the area (1100 trees per ha^{-1} and 24 m^2 ha^{-1} basal area).

To establish a meaningful relationship between physiological variables and remotely sensed data, ground measurements must be collected at the same time of image acquisition. Measurements were taken in summer 2008 (26–27 July) at the same time of AHS data acquisition (8:00 and 10:00 GMT) under uniform clear diffuse skies. The physiological parameter measured per tree was total content of chlorophyll (chlorophyll *a*, *Ca* and chlorophyll *b*, *Cb*). Data analysis was carried out based on the calculation of an average value of chlorophyll content per plot. Within each plot, needles were collected from the top of the stand by selecting branches of illuminated areas from a total four trees per plot. Needles were frozen in liquid nitrogen in the field and then stored at −80 °C prior to determination of chlorophyll *a* and *b* (*Ca* + *b*). Mean pigment content was calculated from a total of 10 young needles (1-year-old needles) collected from the top of the crown. Needle chlorophyll was extracted as reported by Abadía and Abadía (1993). Pigment extracts were obtained from a composed sample made of 5 cm of needle, 1 cm per needle of the same set. Five consecutive centimeters were also cut to take structural measurements (i.e. thickness and width) and determine water content and dry mass. The needles were ground in a mortar on ice with liquid nitrogen and 5 ml of acetone (in the presence of Na ascorbate). After that, the extract was filtered through a 0.45-μm filter to separate pigment extracts from Na ascorbate. Absorption at 470, 644.8, and 661.6 nm was measured with a spectrophotometer to derive chlorophyll *a* and *b* content (Abadía and Abadía, 1993). Additionally, LAI was non-destructively measured in each plot using an LAI-2000 Plant Canopy Analyzer (LICOR Inc., Lincoln, NE, USA; Cutini, 1998). Effective LAI was computed according to the methods used in Dufrêne and Breda (1995). Tree LAI was calculated as the arithmetic average of four LAI measurements taken at 1 m from the tree. In *P. sylvestris*, chlorophyll content ($Ca + b$ μg cm^{-2}) ranged from 22.40 to 53.80 and mean LAI (m^2 m^{-2}) ranged from 1.73 to 4.20 (Table S1, Supporting Information). These values were used to calibrate the DART model as a

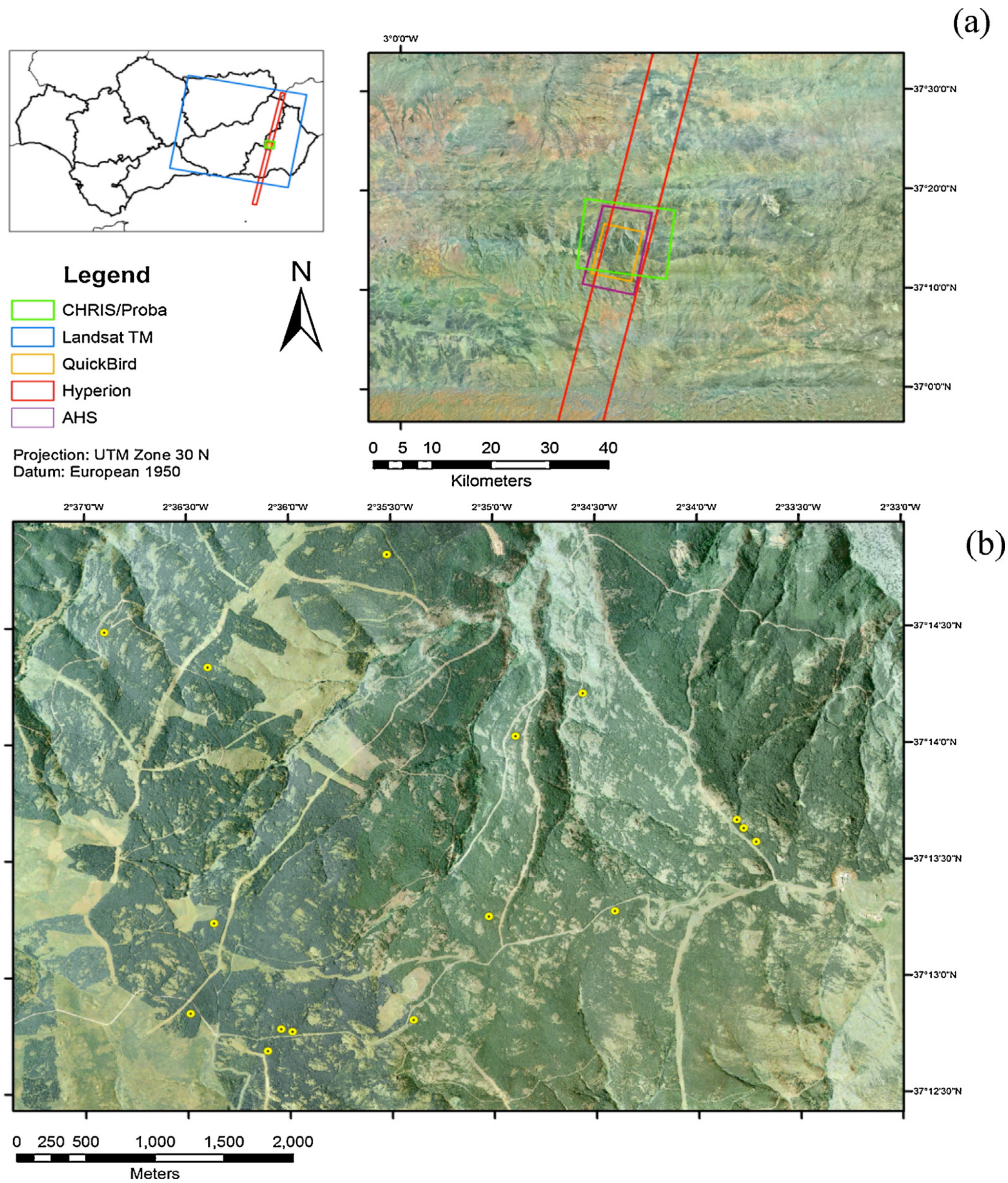

Fig. 1. Airborne footprint of CHRIS/Proba, Landsat TM, QuickBird, Hyperion and AHS sensors (a). Overview of the study area and distribution of *Pinus sylvestris* (white) and *Pinus nigra* (gray) plots on the study area (b).

function of the leaf structural parameter *N*, leaf chlorophyll $a+b$ content, and LAI (leaf area index).

2.3. Image data processing

Remote sensing data acquisition was carried out at the same time of field data collection (chlorophyll measurements) with the exception of Hyperion data, which were acquired 1 month later. AHS, Hyperion, CHRIS/Proba, QuickBird, and Landsat TM images were radiometrically calibrated, converted to surface reflectance, and georeferenced (Table S2, Supporting Information).

Airborne AHS data acquisition was conducted at 12:00 GMT, collecting a 2 m spatial resolution imagery in 38 bands in the Field of View (FOV). Instantaneous Field of View (IFOV) of the AHS sensor were 90° and 2.5 mrad. Plots were located in the central region of the scene in order to avoid edge effects. *At-sensor* radiance processing and atmospheric correction were performed at the National Institute of Aerospatial Technology (INTA) facilities. Atmospheric correction was performed with ATCOR4 based on the MODTRAN radiative transfer model (Berk et al., 1998) using aerosol optical depth at 550 nm collected with a Micro-Tops II sun photometer (Solar Light, Philadelphia, PA, USA). The AHS image rectification was based on the integrated GPS/IMU positioning and navigation systems.

Atmospheric correction of hyperspectral data has a clear advantage over that of multispectral data since the magnitude of water vapor effects in every pixel can be directly assessed from a few spectral channels of the data themselves. Radiometric image processing of satellite image data was carried out based on the specific calibration data of each sensor. Conversion to spectral radiance was achieved in two steps: the value of the corrected pixels was multiplied by the appropriate absolute calibration factor and the result was divided by the effective bandwidth to obtain spectral radiance. The radiometric calibration factor was included in the metadata files of the image. The conversion of radiance to reflectance was based on radiative transfer models. In this study we used ATCOR4 (AIG, 2002), FLAASH, and BEAM 4.6 software (Table S3, Supporting Information).

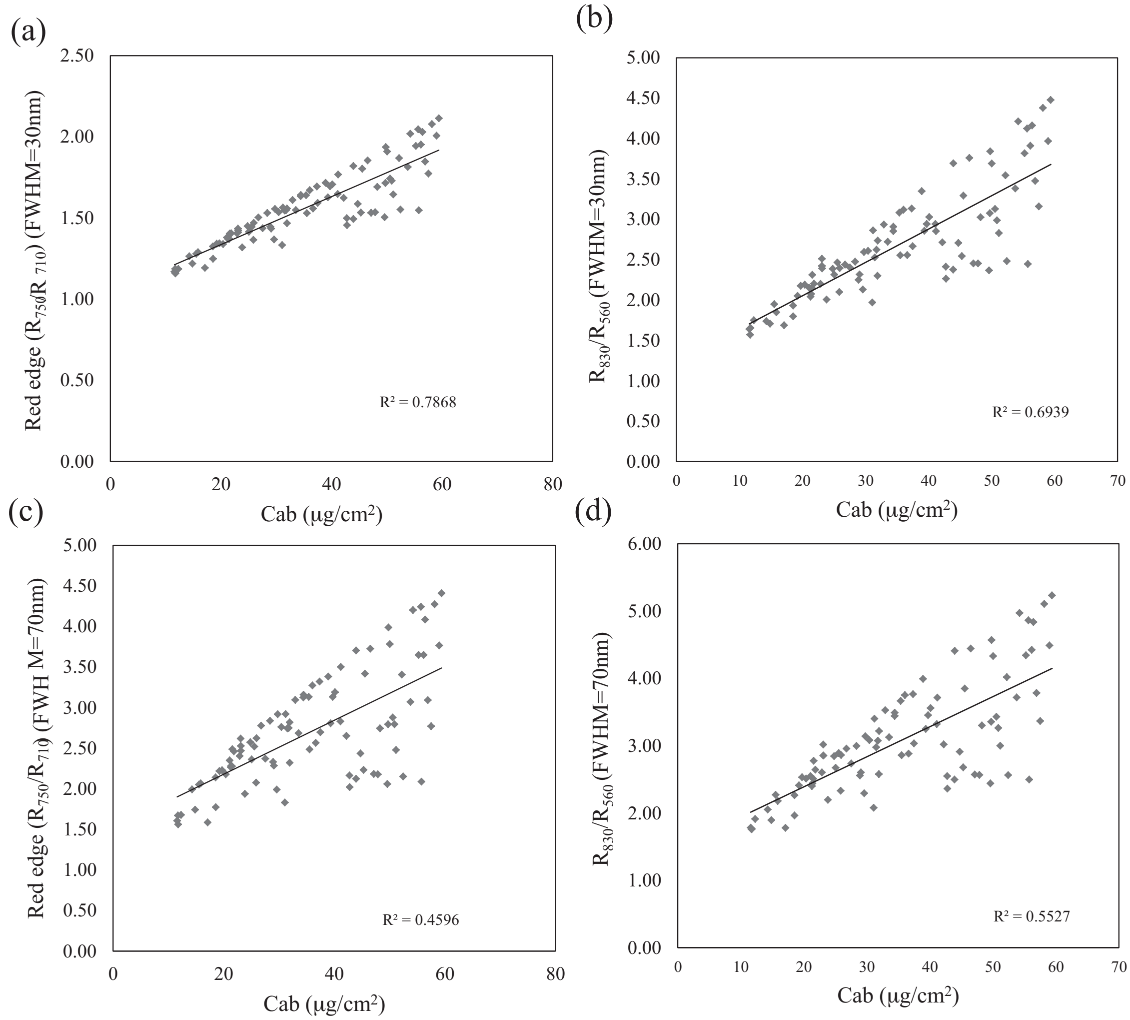

Fig. 2. Relationships obtained between simulated spectral vegetation indices R_{830}/R_{560} (a and c) and red edge (R_{750}/R_{710}) (b and d) and chlorophyll $a + b$ content at 30 nm and 70 nm at the stand level.

The georeferencing process initially started with the processing of the QuickBird image, orthorectified to UTM coordinates (WGS84) using homologous ground control points (GCPs) selected on the image and on digital orthophoto quadrangles of the digital map of Andalucia produced by the *Instituto Geográfico Nacional* (Cohen et al., 2003). Next, the geometrically corrected QuickBird image was used as a reference to correct the images obtained with Landsat TM, Hyperion, and CHRIS/Proba according to the same procedure. Geometric registration of the TM data to the high-resolution data resulted in a root mean square error of position of less than 7 m. The AHS data were co-registered to the QuickBird image (RMSE <2 m) using 30–40 ground control points (Table S3, Supporting Information).

2.4. Simulations with PROSPECT-5 and DART models

A model simulation analysis was conducted to assess the sensitivity of the carotenoid-related optical indices in heterogeneous coniferous forest canopy scenes and to test the performance of new formulations. Radiative transfer modeling methods were applied with the *leaf optical PROperties SPECTra* (PROSPECT-5) model (Jacquemoud and Baret, 1990) coupled with the 3-dimensional Discrete Anisotropic Radiative Transfer (DART) model. Nominal values and the range of parameters used for leaf and stand modeling are summarized in Tables S4 and S5 (Supporting Information).

For the leaf-level simulations, PROSPECT-5 was selected. This model simulates leaf directional-hemispherical reflectance and transmittance from the 400 to the 2500 nm spectral region with five input variables: chlorophyll *a* and *b* (*Cab*), carotenoids (*Car*), leaf *dry* matter (*Cm*), equivalent water thickness (EWT) and the leaf structure parameter (*N*) (Feret et al., 2008). Although PROSPECT was originally developed for broad leaves, it has also been validated and is widely used for needles (Moorthy et al., 2008). At the stand level, we chose DART because it simulates radiative transfer over complex structures; we used it to generate coniferous canopy architectures at high spatial resolution (Gastellu-Etchegorry et al., 1999). DART has been used to simulate heterogeneous coniferous forest canopies (Malenovský et al., 2008). In order to simulate the forest canopy architecture of the study sites under study, the DART model was parameterized based on detailed field measurements. Measured reflectance spectra were generally typical of healthy green foliage and were higher for QuickBird compared to Landsat TM and AHS in the range values between 500 and 800 nm (Fig. S1, Supporting Information).

2.5. Vegetation indices and correlation analysis

Several optical indices reported in the literature have been proven to be well correlated with chlorophyll content (Main et al., 2011). Gitelson and Merzlyak (1997) observed high sensitivity of

Table 1
Vegetation indices used in the study.

Sensor	Vegetation index, chlorophyll
QuickBird	R_{830}/R_{560}
Landsat TM	R_{830}/R_{560}
CHRIS/Proba	R_{804}/R_{563}
Hyperion	R_{803}/R_{569}
AHS	R_{803}/R_{571}

reflectance near bands 550 and 700 nm to Ch content. Those authors proposed several indices utilizing spectral features located on these bands for estimation of Ch content. In this study, we used simple ratios based on the green chl index of NIR to red reflectance related to the near bands 550 ($SR = R_{800}/R_{560}$) (Gitelson et al., 1996, 2005). Bands selection was done considering the spectral resolution of the sensors used on this research (Table 1). Once this simple ratio (SR) was assessed using a PROSPECT5-DART model, five simple ratio indices based on the green reflectance for chlorophyll estimation were computed from the canopy spectra according to spectral sensor resolution (Table 1) (Zarco-Tejada et al., 2004; Main et al., 2011). The original indices included in this study had as target parameter the total chlorophyll (i.e. $Ca+b$), as well as the plant levels (i.e. canopy or leaf). Those vegetation indices were calculated using AHS data for *P. sylvestris* stands and the rest of sensors for *Pinus* stands.

Linear regressions between chlorophyll content and spectral indices derived from broad-band multispectral vs. narrow-band hyperspectral imagery were used to compute the model's coefficient of determination (r^2) and prediction error (root mean square error, RMSE) for leaf chlorophyll content. These two measures were chosen because they are commonly reported to be part of regression analyses and are easy to interpret (Stenberg et al., 2003).

3. Results

3.1. Modeling results

Based on the infinite reflectance models and 3-D model simulations, the spectra for the red-edge (R_{750}/R_{710}) and simple ratio (R_{800}/R_{560}) indices were tested with the PROSPECT-5+DART model independently within the FWHM wavelength range of 30 and 70 nm. Both indices showed good fit to estimated values of $Ca+b$ content in the 30 nm range using either index ($r^2 = 0.78$, $P < 0.001$ and $r^2 = 0.69$, $P < 0.001$, respectively) (Fig. 2). However, the determination coefficient decreased significantly when a FWHM of 70 nm was used, yielding results of $r^2 = 0.45$ ($P < 0.001$) for the red-edge R_{750}/R_{710} index and $r^2 = 0.55$ ($P < 0.001$) for the R_{800}/R_{560} vegetation index (Fig. 2), although regressions were significant.

3.2. Experimental results

In high-resolution AHS images, ground-measured average needle $Ca+b$ content was found to be significantly correlated with the red-edge R_{750}/R_{710} vegetation index ($r^2 = 0.72$, $P = 0.004$) and with chlorophyll $a+b$ content ranging from 14.41 µg/cm^2 to 53.31 µg/cm^2 (Fig. 3). Chlorophyll estimation using the simple ratio R_{830}/R_{571} index extracted at stand level had an accuracy of $r^2 = 0.65$ ($P = 0.008$). Chlorophyll $a+b$ content for the Scots pine cover was estimated from the re-sampled 30-m resolution AHS image (Figs. 4 and 5). Chlorophyll $a+b$ content was found to be significantly correlated with the simple ratio R_{830}/R_{571} index ($r^2 = 0.63$, $P = 0.011$).

Fig. 5 shows the results obtained for the estimation of $Ca+b$ content at stand level for Scots pine stands using the four spectral resolutions and the various indices assessed. Broad-band multispectral sensors such as QuickBird and Landsat showed low r^2

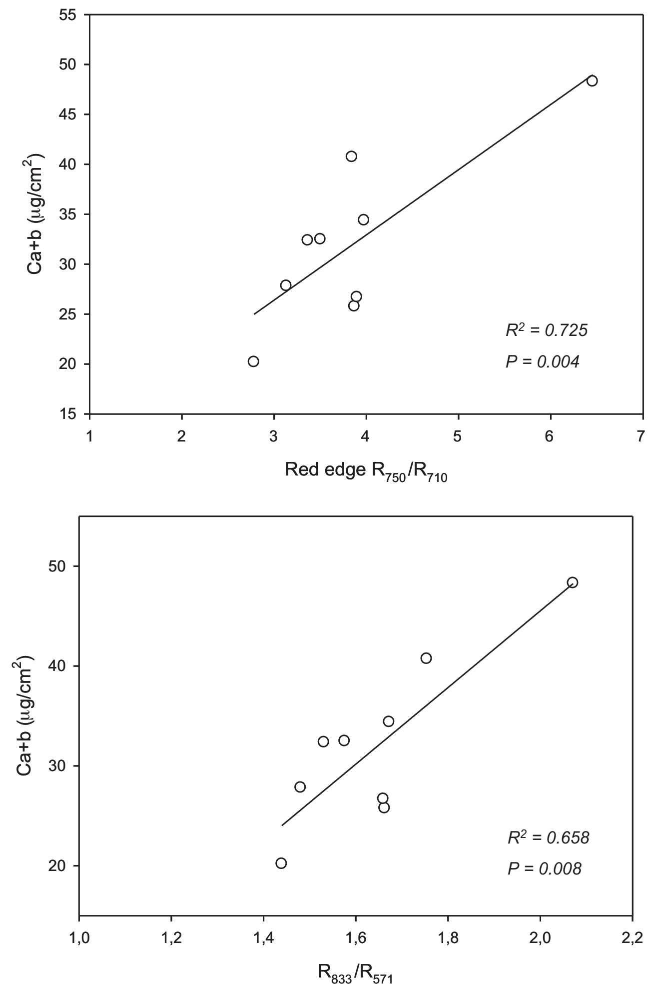

Fig. 3. Relationships between $Ca+b$ concentration and chlorophyll vegetation indices red edge (R_{750}/R_{710}) (a) and R_{833}/R_{571} (b) for *Pinus sylvestris* derived from AHS sensor. Mean values obtained from 2 m spatial resolution at stand level.

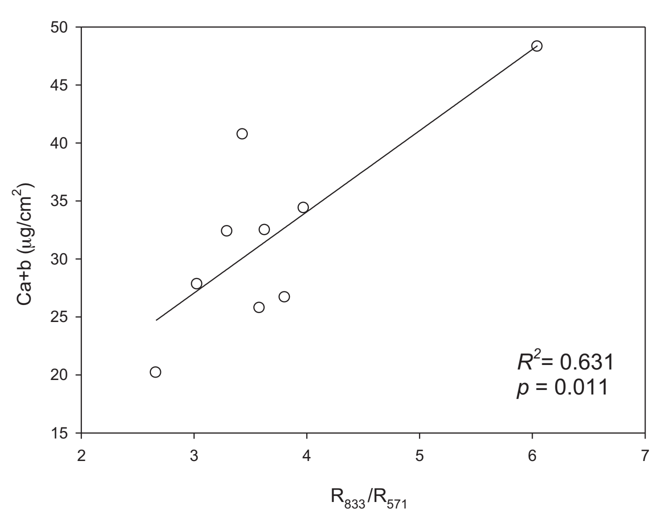

Fig. 4. Relationships between $Ca+b$ concentration and R_{833}/R_{571} (b) derived from AHS sensor for *Pinus sylvestris*. Mean values obtained from 30 m spatial resolution at stand level.

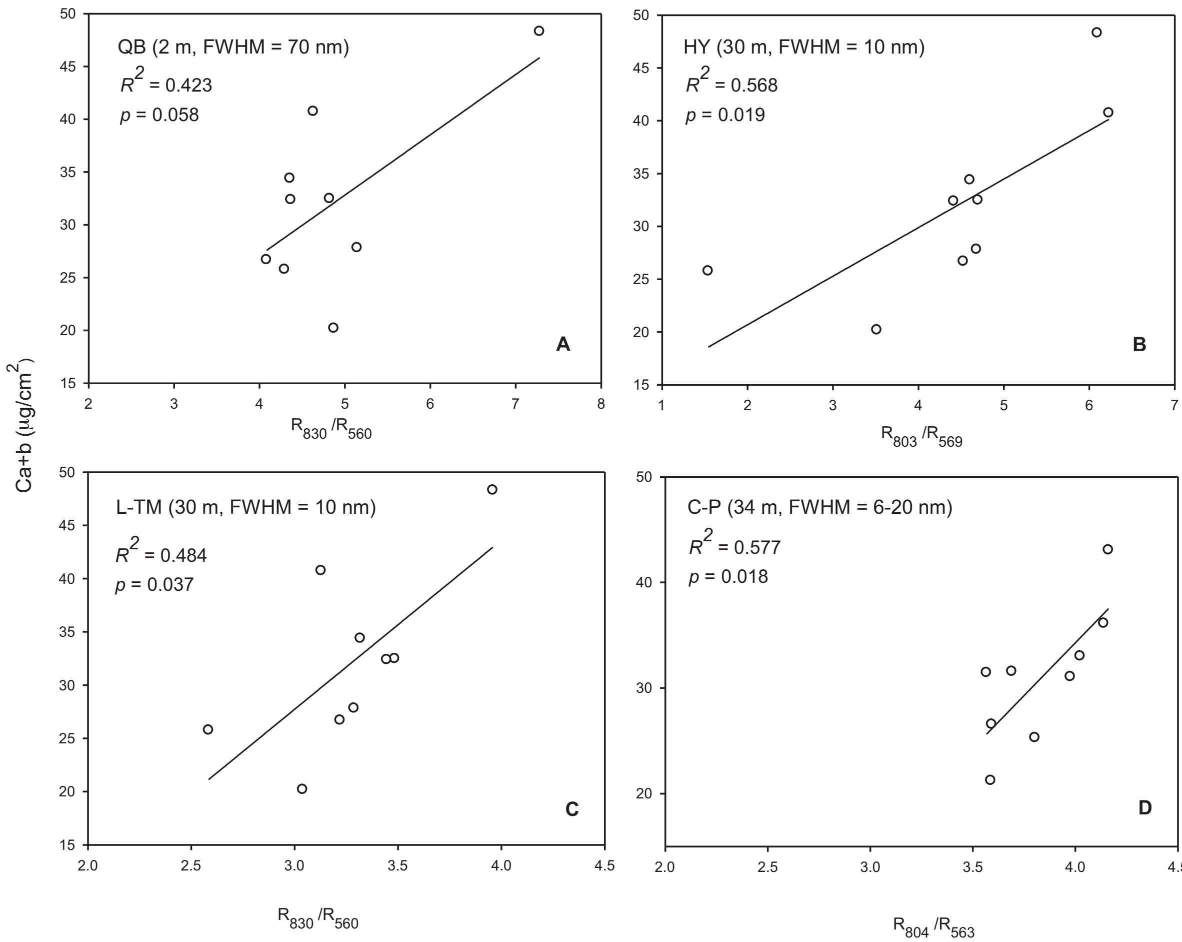

Fig. 5. Relationships between Cab concentration and Chlorophyll vegetation indices derived from multispectral satellite sensors (Quick Bird (a), Landsat TM (c)) and hyperspectral sensors (Hyperion (b), CHRIS/Proba (d)) for *Pinus sylvestris stands*.

values ($r^2 = 0.42$, $P = 0.058$ and $r^2 = 0.48$, $P = 0.037$ respectively). By contrast, narrow-band hyperspectral sensors such as Hyperion and CHRIS/Proba showed the strongest relationships ($r^2 = 0.56$, $P = 0.019$ and $r^2 = 0.57$, $P = 0.018$ respectively).

3.3. *Chlorophyll cartography*

Fig. 6 shows maps of estimated $Ca+b$ values produced by linear interpolation from image data in the range of 14.41 μg/cm^2 to 53.31 μg/cm^2 using the simple ratio vegetation indices acquired from Hyperion, CHRIS/Proba, QuickBird, and Landsat TM images. Mapping results enabled the estimation of $Ca+b$ content at the stand level for the entire scene showing the spatial variability of chlorophyll content, as there were areas with high (>27.5 μg/cm^2) and low (<μg/cm^2) chlorophyll content. Higher contents were evidently found along the healthy areas and riversides.

4. Discussion

Forest biophysical data retrieval is required for forest managers to make appropriate economic and environmental management decisions. Chlorophyll content ($Ca+b$) is a key biophysical variable controlling many biological processes such as photosynthesis, transpiration, and energy balance of terrestrial ecosystems (Blackburn, 2007; Warning and Running, 2007). Changes in leaf chlorophyll content result in variations of leaf reflectance and transmittance spectra in the visible region, which contribute to canopy reflectance (Blackburn, 2007). Canopy reflectance is also strongly affected by other factors such as canopy architecture, chlorophyll distribution in the canopy, sun/view angle, and forest background. Because of this ecological relevance, chlorophyll content maps are increasingly used as input to model biogeochemical processes and to detect stress in order to enable remedial action to be planned (Carter and Knapp, 2001; Gitelson et al., 2003). Remote sensing data has been recognized as a reliable method for estimating ecophysiological variables of vegetation (Cohen et al., 2003; Hernández-Clemente et al., 2012). This study addresses this complex issue by comparing radiation transfer models with empirical correlations of chlorophyll content.

Radiative transfer (RT) models take into account complex canopy structural effects and the leaf model considers light interactions with the foliar medium and the complexity of leaf internal structure. The PROSPECT model and a more complex approach such as the coupled PROSPECT + DART (Discrete Anisotropic Radiative Transfer) model have been used to predict the chlorophyll content of heterogeneous coniferous forests (Gastellu-Etchegorry et al., 1999, 2004; Zarco-Tejada et al., 2004). In this study, the PROSPECT + DART model provided good predictions of $Ca+b$ in *P. sylvestris* forests using the red-edge and simple ratio R_{830}/R_{571} indices at two different spectral resolutions, 30 nm ($r^2 = 0.76$ and $r^2 = 0.69$ respectively) and 70 nm ($r^2 = 0.45$ and $r^2 = 0.55$ respectively). The promising results obtained with the PROSPECT + DART radiative transfer model using the alternative simple ratio R_{830}/R_{571}

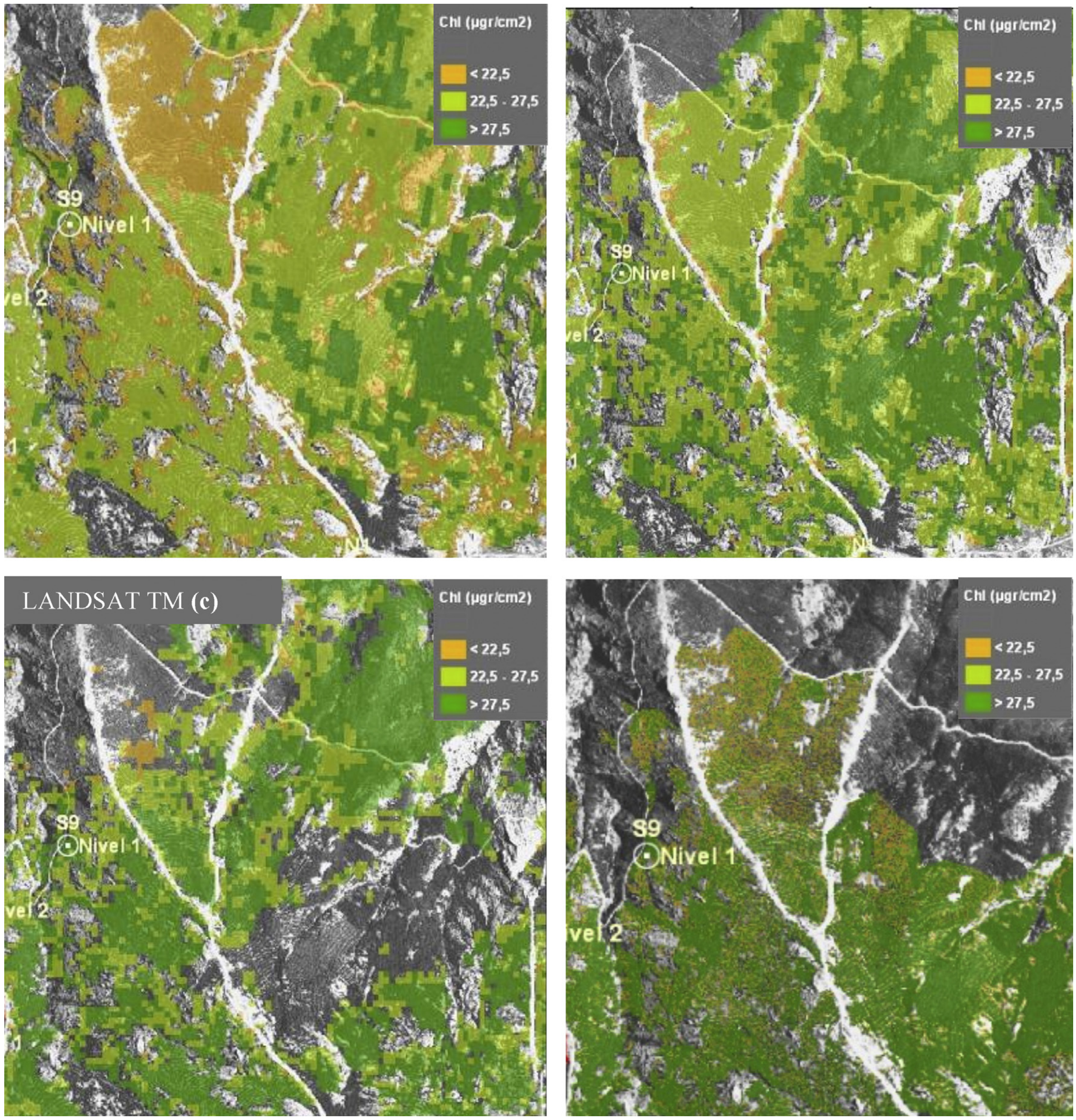

Fig. 6. Maps showing the spatial variation of $Ca+b$ content mg/cm2 using the R_{833}/R_{570} index and based on the CHRIS/Proba (a), Hyperion (b), Landsat (c) and AHS (d) image information.

index suggest that this index may provide a valuable method to derive canopy $Ca+b$ from multispectral and hyperspectral sensors at the canopy scale.

Experimental results obtained analyzing multi- and hyperspectral sensor data with red-edge and simple ratio indices were then correlated with $Ca+b$ in *P. sylvestris* forests, as in other studies (Gitelson and Merzlyak, 1997; Yao et al., 2010). In this study, vegetation indices were particularly accurate at estimating chlorophyll content ($Ca+b$) with AHS data using the red-edge and simple ratio R_{830}/R_{571} indices (2 m, $r^2=0.72$ and $r^2=0.65$ respectively). With the new commercial satellite systems, red-edge bands are available for estimating chlorophyll content (Ramoelo et al., 2012). However, broad-band multispectral and narrow-band hyperspectral data are widely available and low-cost sensors may not have a red-edge band. In this study, the simple ratio extracted at stand level showed a significant relationship with canopy chlorophyll $a+b$ content (AHS $r^2=0.63$, $P=0.011$; QuickBird $r^2=0.42$, $P=0.058$, Landsat TM $r^2=0.48$, $P=0.037$, Hyperion $r^2=0.56$, $P=0.019$, and CHRIS/Proba $r^2=0.57$, $P=0.018$) for forest plantations at a spatial scale that corresponds to a typical area of pine forest stands in southern Spain. However, variability of SR responses may be related to the understory, especially for typical open and clumped Mediterranean pine stands. Understory vegetation tends to increase the NIR and can therefore lead to an overestimation of chlorophyll. The near infrared reflectance of bare soil can also alter the SR response; such situation will potentially be mixed into the analysis, especially for vegetation with low chlorophyll values.

Identifying variability in chlorophyll content in order to map and monitor forest canopy stress is a potential means of adopting sustainable forest management. Chlorophyll content maps provide key information for identification of risk decline areas within the field (Mohammed et al., 2000). Use of remote sensing-derived maps for timely assessment of vegetation conditions in Mediterranean forests can help forest managers to undertake a rapid assessment of forest conditions at times of 'climatic risk' and to correct stress conditions or early degradation in forests, thus reducing their impact on mortality and helping time-critical management (Hernández-Clemente et al., 2012). In southern Spain, forest decline process have been observed over the last few years and forest managers have taken decisions using 'output maps' based on visual observation as their field maps (Navarro-Cerrillo et al., 2007). A new generation of biophysical maps of areas where the forest is showing growth decline processes may help to identify areas with poor performance; output images can be used as a field guide to locate and analyze the causes of variability within and between forests stands. To predict *Ca* + *b* in large forest areas, SR seems useful to produce exploratory maps of pine forest species using hyperspectral and multispectral images (Tian et al., 2002; Hernández-Clemente et al., 2012) in order to detect forest canopy variability at an early stage of damage development. As each sensor has its limitations, the selection of a given one depends on the particular application it will be used for. As pointed out in the results, the canopy indices proposed in this research were modified to include off-chlorophyll absorption wavebands in the 680 or 800 nm regions. High-resolution hyperspectral CHRIS/Proba and Hyperion sensors are potential data sources for biochemical parameter extraction from vegetated targets. By contrast, multispectral images showed less reliable but significant results for obtaining biophysical variables (Main et al., 2011). This is particularly attractive, since Hyperion networks provide a powerful means of analyzing complex forest covers with a good cost/labor ratio.

Additionally, with the future launch of the hyperspectral/spaceborne missions as EnMAP and Hyspiri, a new hyperspectral sensor with high signal-to-noise ratio at medium spatial resolution will become available (van der Meer et al., 2012). The Sentinel-2 wide-swath high-resolution multispectral system will provide improved continuity for Spot- and Landsat-type observations, with high spatial, spectral and temporal resolution, and radiometric and geometric image quality. In comparison to the latter sensors, Sentinel-2 incorporates three new spectral bands in the red-edge region, which are centered at 705, 740 and 783 nm, which can be used for the retrieval and monitoring of LAI and chlorophyll content (Delegido et al., 2011; Clevers and Gitelson, 2013). Those sensors will offer new potential contributions of the chlorophyll and pigments evaluation on forest canopies. Data form these new high-resolution multispectral and hyperspectral satellite can subsequently be used to improve biophysical indicators, such as chlorophyll cartography as a promising field of investigation taking advantage of spatial coverage and revisit capability of these sensors.

5. Conclusions

This research shows the feasibility of using high and medium spatial resolution remote sensing observations to estimate chlorophyll content at forest canopy scale. At this scale, *Ca* + *b* content can be estimated using a SR (R_{830}/R_{571}) vegetation index based on modeling (PROSPECT-5 + DART) and experimental results. With a large enough range in physiological conditions (i.e. chlorophyll content), scaling-up methodologies offer an operational approach to forest condition rating. High-resolution hyperspectral CHRIS/Proba and Hyperion sensors are potential data sources for biochemical parameter extraction from vegetated targets. By contrast, multispectral images showed less reliable but significant results for obtaining biophysical variables.

Maps of physiological conditions are useful to distinguish healthy from stressed pine stands and are good *bioindicators* of stand health condition. However, these applications still require fieldwork to support remote sensing data. Although the use of SR does not yield a totally predictive algorithm for chlorophyll estimation (r^2 = 0.42–0.57), the general correlations indicate that it is feasible to assess forest stand condition using vegetation indexes. The data presented here provide good evidence that multispectral and hyperspectral remote sensing approaches may have real potential for estimating the chlorophyll content of forest canopies. Despite the limitations of the radiative transfer model assumptions, the PROSPECT5 + DART produced satisfactory results for pine forests. This shows the feasibility of using medium spatial resolution remote sensing data to obtain biophysical parameters in forests using variables and indices that minimize the effect of forest structure. The generation of biochemical maps at the stand level could play a critical role in the early detection of forest decline processes enabling their application in precision forestry. These results open new possibilities for the monitoring of physiological processes with medium-resolution sensors.

Acknowledgments

This study was supported by DIVERBOS (CGL2011-30285-C02-02). We also acknowledge the financial support of the University of Cordoba-*Campus de Excelencia CEIA3*. Rafael Sánchez, David Ariza, and Francisco Ruiz are acknowledged for their measurements and technical support in the field campaigns. Finally, we greatly appreciate the support of J.P. Gastellu-Etchegorry with the DART 3-D radiative transfer model.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jag.2013.06.001.

References

Abadía, A., Abadía, J., 1993. Iron and plant pigments. In: Barton, L.L., Hemming, B.C. (Eds.), Iron Chelation in Plants and Soil Microorganisms. Academic, San Diego, pp. 327–344.
AIG, 2002. ACORN 4.0 User's Guide ENVI Plug-in Version. Analytical Imaging and Geophysics LLC ACORN Version 4.0, Edition, Boulder, USA.
Berk, A., Bernstein, L.S., Anderson, G.P., Acharya, P.K., Robertson, D.C., Chetwynd, J.H., Adler-Golden, S.M., 1998. MODTRAN cloud and multiple scattering upgrades with application to AVIRIS. Remote Sensing of Environment 65, 367–375.
Blackburn, G.A., 2007. Hyperspectral remote sensing of plant pigments. Journal of Experimental Botany 58, 855–867.
Carter, G.A., Knapp, A.K., 2001. Leaf optical properties in higher plants: linking spectral characteristics to stress and chlorophyll content. American Journal of Botany 88, 677–684.
Carter, G.A., 1994. Ratios of leaf reflectances in narrow wavebands as indicators of plant stress. International Journal of Remote Sensing 15, 697–704.
Clevers, J.G.P.W., Gitelson, A.A., 2013. Remote estimation of crop and grass chlorophyll and nitrogen content using red-edge bands on Sentinel-2 and -3. International Journal of Applied Earth Observation 23, 344–351.
Cohen, W.B., Maierpserger, T.K., Gower, S.T., Turner, D.P., 2003. An improved strategy for regression of biophysical variables and LandsatETM+ data. Remote Sensing of Environment 84, 561–571.
Cutini, A., Matteucci, G., Mugnozza, G.S., 1998. Estimation of leaf area index with the Li-Cor LAI 2000 in deciduous forests. Forest Ecology and Management 105 (1–3), 55–65.
Daughtry, C.S., Walthall, C.L., Kim, M.S., de Colstoun, E.B., McMurtrey III, J.E., 2000. Estimating corn leaf chlorophyll content from leaf and canopy reflectance. Remote Sensing of Environment 74 (2), 229–239.
Delalieux, S., Somers, B., Verstraeten, W., van Aardt, J., Keulemans, W., Coppin, P., 2009. Hyperspectral indices to diagnose leaf biotic stress of apple plants, considering leaf phenology. International Journal of Remote Sensing 30, 1887–1912.
Delegido, J., Verrelst, J., Alonso, L., Moreno, J., 2011. Evaluation of sentinel-2 red-edge bands for empirical estimation of green LAI and chlorophyll content. Sensors 11, 7063–7081.
Demarez, V., Gastellu-Etchegorry, J.P., 2000. A modelling approach for studying forest chlorophyll content. Remote Sensing of Environment 71, 226–238.
Deshayes, M., Guyon, D., Jeanjean, H., Stach, N., Jolly, A., Hagolle, O., 2006. The contribution of remote sensing to the assessment of drought effects in forest ecosystems. Annals of Forest Science 63, 579–595.
Dufrêne, E., Breda, N., 1995. Estimation of deciduous forest leaf area index using direct and indirect methods. Oecologia 104, 156–162.
Gastellu-Etchegorry, J.P., Guillevic, P., Zagolski, F., Demarez, V., Trichon, V., Deering, D., Leroy, M., 1999. Modeling BRF and radiation regime of boreal and tropical forests: I. BRF. Remote Sensing of Environment 68, 281–316.
Gastellu-Etchegorry, J.P., Martin, E., Gascon, F., 2004. Dart: a 3D model for simulating satellite images and studying surface radiation budget. International Journal of Remote Sensing 25, 73–96.
Gitelson, A., Merzlyak, M., 1997. Remote estimation of chlorophyll content in higher plant leaves. International Journal of Remote Sensing 18, 2691–2698.

Gitelson, A.A., Gritz, Y., Merzlyak, M.N., 2003. Relationships between leaf chlorophyll content and spectral reflectance and algorithms for non-destructive chlorophyll assessment in higher plant leaves. Journal of Plant Physiology 160, 271–282.
Gitelson, A.A., Merzlyak, M.N., Grits, Y., 1996. Novel algorithms for remote sensing of chlorophyll content in higher plant leaves. Papers in Natural Resources: Remote Sensing for a Sustainable Future IEEE 4, 2355–2357.
Gitelson, A.A., Viña, A., Rundquist, D.C., Ciganda, V., Arkebauer, T.J., 2005. Remote estimation of canopy chlorophyll content in crops. Geophysical Research Letters 32, L08403.
Gong, P., Pu, R., Heald, R.C., 2002. Analysis of in situ hyperspectral data for nutrient estimation of giant sequoia. International Journal of Remote Sensing 23, 1827–1850.
Hernández-Clemente, R., Navarro-Cerrillo, R.M., Zarco-Tejada, P.J., 2012. Carotenoid content estimation in an heterogeneous conifer forest using narrow-band indices and PROSPECT + DART simulations. Remote Sensing of Environment 127, 298–315.
Jacquemoud, S., Baret, F., 1990. PROSPECT: a model of leaf optical properties spectra. Remote Sensing of Environment 34, 75–91.
Lichtenthaler, H.K., 1996. Vegetation stress: an introduction to the stress concept in plants. Journal of Plant Physiology 148, 4–14.
Main, R., Cho, M.A., Mathieu, R., O'Kennedy, M.M., Ramoelo, A., Koch, S., 2011. An investigation into robust spectral indices for leaf chlorophyll estimation. ISPRS Journal of Photogrammetry 66, 751–761.
Malenovský, Z., Homolova, L., Cudlin, P., Zurita Milla, R., Schaepman, M.E., Clevers, J.G., Martin, E., Gastellu-Etchegory, J.P., 2008. Physically-based retrievals of Norway spruce canopy variables from very high spatial resolution hyperspectral data. Geoscience and Remote Sensing Symposium 1, 4057–4060.
Malenovský, Z., Homolová, L., Zurita-Milla, R., Lukeš, P., Kaplan, V., Hanuš, J., Gastellu-Etchegorry, J.P., Schaepman, M.E., 2013. Retrieval of spruce leaf chlorophyll content from airborne image data using continuum removal and radiative transfer. Remote Sensing of Environment 131, 85–102.
Feret, J.P., François, C., Asner, G.P., Gitelson, A.A., Martin, R.E., Bidel, L.P., Ustin, S.L., Maire, G., Jacquemoud, S., 2008. PROSPECT-4 and 5 advances in the leaf optical properties model separating photosynthetic pigments. Remote Sensing of Environment 112, 3030–3043.
Mohammed, G.H., Noland, T.L., Irving, D., Sampson, P.H., Zarco-Tejada, P.J., Miller, J.R., 2000. Natural and stress-induced effects on leaf spectral reflectance in Ontario species. Sault Ste. Marie, Ministry of Natural Resources, Ontario Forest Research Institute, Forest Research Report 156, 1–34.
Moorthy, I., Miller, J.R., Noland, T.L., 2008. Estimating chlorophyll content in conifer needles with hyperspectral data: an assessment at the needle and canopy level. Remote Sensing of Environment 112, 2824–2838.
Navarro-Cerrillo, R.M., Varo, M.A., Lanjeri, S., Hernández-Clemente, R., 2007. Cartografía de defoliación en los pinares de pino silvestre (*Pinus sylvestris* L.) y pino salgareño (*Pinus nigra* Arnold) en la Sierra de los Filabres. Ecosistemas 16, 163–171.
Peñuelas, J., Baret, F., Filella, I., 1995. Semi-empirical indices to assess carotenoids/chlorophyll *a* ratio from leaf spectral reflectance. Photosynthetica 31, 221–230.
Ramoelo, A., Skidmore, A.K., Cho, M.A., Schlerf, M., Mathieu, R., Heitkönig, I.M., 2012. Regional estimation of savanna grass nitrogen using the red-edge band of the spaceborne RapidEye sensor. International Journal of Applied Earth Observation 19, 151–162.
Schütz, J., 1997. Sylviculture 2 – La gestion des forêts irrégulières et mélangées. Presses Polytechniques et Universitaires Romandes, Lausanne, pp. 168.
Sims, D., Gamon, J., 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. Remote Sensing of Environment 81, 337–354.
Stenberg, P., Nilson, T., Smolander, H., Voipio, P., 2003. Gap fraction based estimation of LAI in Scots pine stands subjected to experimental removal of branches and stems. Canadian Journal of Remote Sensing 29, 363–370.
Tian, Y., Woodcock, C., Wang, Y., Privette, J., Shabanov, N., Zhou, L., Zhang, Y., Buermann, W., Dong, J., Veikkanen, D., Hame, T., Andersson, K., Ozdogan, M., Knyazikhin, Y., Myneni, R., 2002. Multiscale analysis and validation of the MODIS LAI product. I. Uncertainty assessment. Remote Sensing of Environment 83, 414–430.
Tomppo, E., Olsson, H., Ståhl, G., Nilsson, M., Hagner, O., Katila, M., 2008. Combining national forest inventory field plots and remote sensing data for forest databases. Remote Sensing of Environment 112, 1982–1999.
Ustin, S.L., Gitelson, A.A., Jacquemoud, S., Schaepman, M., Asner, G.P., Gamon, J.A., Zarco-Tejada, P., 2009. Retrieval of foliar information about plant pigment systems from high resolution spectroscopy. Remote Sensing of Environment 113, S67–S77.
van der Meer, F.D., van der Werff, H.M.A., van Ruitenbeek, F.J.A., Hecker, C.A., Bakker, W.H., Noomen, M.F., van der Meijde, M., Carranza, E.J.M., Smeth, J.B., Woldai, d.T., 2012. Multi- and hyperspectral geologic remote sensing: a review. International Journal of Applied Earth Observation 14, 112–128.
Verrelst, J., Schaepman, M.E., Malenovský, Z., Clevers, J.G., 2010. Effects of woody elements on simulated canopy reflectance: implications for forest chlorophyll content retrieval. Remote Sensing of Environment 114, 647–656.
Warning, R.H., Running, S.W., 2007. Forest Ecosystems Analysis at Multiple Scales, 3rd ed. Elsevier, Netherlander.
Wu, C., Niu, Z., Tang, Q., Huang, W., Rivard, B., Feng, J., 2009. Remote estimation of gross primary production in wheat using chlorophyll-related vegetation indices. Agricultural and Forest Meteorology 149, 6–7.
Yao, X., Zhu, Y., Tian, Y., Feng, W., Cao, W., 2010. Exploring hyperspectral bands and estimation indices for leaf nitrogen accumulation in wheat. International Journal of Applied Earth Observation 12, 89–100.
Zarco-Tejada, P.J., Miller, J.R., Mohammed, G.H., Noland, T.L., Sampson, P.H., 2001. Scaling-up and model inversion methods with narrow-band optical indices for chlorophyll content estimation in closed forest canopies with hyperspectral data. IEEE Transactions on Geoscience and Remote Sensing 39, 1491–1507.
Zarco-Tejada, Z., Miller, J., Harron, J., Hu, B., Noland, T., Goel, N., 2004. Needle chlorophyll estimation through model inversion using hyperspectral data for boreal conifer forest canopies. Remote Sensing of Environment 89, 189–199.
Zarco-Tejada, P.J., Ustin, S.L., Whiting, M.L., 2005. Temporal and spatial relationships between within-field yield variability in cotton and high-spatial hyperspectral remote sensing imagery. Agronomy Journal 97, 641–653.