ELSEVIER

Remote Sensing of Environment 85 (2003) 109–124

Remote Sensing of Environment

www.elsevier.com/locate/rse

Water content estimation in vegetation with MODIS reflectance data and model inversion methods

P.J. Zarco-Tejada*, C.A. Rueda, S.L. Ustin

Department of Land, Air and Water Resources (LAWR), Center for Spatial Technologies and Remote Sensing (CSTARS), Veihmeyer Hall, University of California, Davis, Davis, CA 95616, USA

Received 13 May 2002; received in revised form 7 November 2002; accepted 9 November 2002

Abstract

Statistical and radiative-transfer physically based studies have previously demonstrated the relationship between leaf water content and leaf-level reflectance in the near-infrared spectral region. The successful *scaling up* of such methods to the canopy level requires modeling the effect of canopy structure and viewing geometry on reflectance bands and optical indices used for estimation of water content, such as normalized difference water index (NDWI), simple ratio water index (SRWI) and plant water index (PWI). This study conducts a radiative transfer simulation, linking leaf and canopy models, to study the effects of leaf structure, dry matter content, leaf area index (LAI), and the viewing geometry, on the estimation of leaf equivalent water thickness from canopy-level reflectance. The applicability of radiative transfer model inversion methods to MODIS is studied, investigating its spectral capability for water content estimation. A modeling study is conducted, simulating leaf and canopy MODIS-equivalent synthetic spectra with random input variables to test different inversion assumptions. A field sampling campaign to assess the investigated simulation methods was undertaken for analysis of leaf water content from leaf samples in 10 study sites of chaparral vegetation in California, USA, between March and September 2000. MODIS reflectance data were processed from the same period for equivalent water thickness estimation by model inversion linking the PROSPECT leaf model and SAILH canopy reflectance model. MODIS reflectance data, viewing geometry values, and LAI were used as inputs in the model inversion for estimation of leaf equivalent water thickness, dry matter, and leaf structure. Results showed good correlation between the time series of MODIS-estimated equivalent water thickness and ground measured leaf fuel moisture (LFM) content ($r^2 = 0.7$), demonstrating that these inversion methods could potentially be used for global monitoring of leaf water content in vegetation.

Keywords: Radiative transfer; Water content; Leaf fuel moisture; Equivalent water thickness; MODIS; Reflectance; Model inversion

1. Introduction

Quantitative estimation of leaf biochemical and canopy biophysical variables is a key element to the successful application of remote sensing in vegetation monitoring, a major goal in terrestrial ecology and a long-term research objective given the complexity of the vegetation canopies and phenomena (Goetz, Gao, & Wessman, 1992; Verstraete, Pinty, & Myneni, 1994). Accurate estimates of leaf pigments, nitrogen, dry matter, water content, and leaf area index (LAI) from remote sensing can assist in determining vegetation physiological status (Carter, 1994; Peñuelas, Gamon, Fredeen, Merino, & Field, 1994), the study of species and seasonal dependence (e.g., Belanger, Miller, & Boyer, 1995), and may serve as bioindicators of vegetation stress (e.g., Luther & Carroll, 1999; Zarco-Tejada, Miller, Noland, Mohammed, & Sampson, 2001). The remote determination of one of these biochemical constituents, vegetation water content, has important implications in agriculture and forestry (Gao & Goetz, 1995), it is essential for drought assessment in natural vegetation (Peñuelas, Filella, Biel, Serrano, & Savé, 1993), and it is a major driver in predicting the susceptibility to fire (Chandler, Cheney, Thomas, Trabaud, & Williams, 1983; Pyne, Andrews, & Laven, 1996; Ustin et al., 1998).

Abbreviations: C_{a+b}, chlorophyll a+b; C_m, dry matter; C_w, leaf equivalent water thickness; N, leaf internal structure; NDWI, normalized difference water index $(R_{860}-R_{1240})/(R_{860}+R_{1240})$; SRWI, simple ratio water index (R_{858}/R_{1240}); LAI, leaf area index; t_s, sun angle; t_v, view angle; p_s, relative azimuth angle; dw, dry weight; fw, fresh weight; LFM, leaf fuel moisture.

* Corresponding author. Escuela Técnica Superior de Ingenierías Agrarias, Campus de La Yutera, Universidad de Valladolid, Avda. de Madrid, 44, 34004 Palencia, Spain.

E-mail address: pzarco@iaf.uva.es (P.J. Zarco-Tejada).

0034-4257/03/$ - see front matter © 2003 Elsevier Science Inc. All rights reserved.
doi:10.1016/S0034-4257(02)00197-9

Several studies demonstrate the existing link between leaf-level reflectance in the 400–2500 nm spectral region and the amount of water in the leaf through optical indices, regression analysis and radiative transfer modeling (Aldakheel & Danson, 1997; Allen, Gausman, Richardson, & Cardenas, 1971; Carter, 1991, 1993; Ceccato, Flasse, Tarantola, Jacquemoud, & Gregoire, 2001; Danson, Steven, Malthus, & Clarck, 1992; Gausman, Allen, Cardenas, & Richarson, 1970; Hunt, Rock, & Nobel, 1987; Jacquemoud & Baret, 1990). The primary and secondary effects of water content on leaf reflectance were studied by Carter (1991) showing that sensitivity of leaf reflectance to water content was greatest in spectral bands centered at 1450, 1940, and 2500 nm. Indirect effects of water content on reflectance were also found at 400 nm, in the red edge at 700 nm (Filella & Peñuelas, 1994) and on vegetation indices such as NDVI (Roberts, Green, & Adams, 1997). The effects of leaf structure on the water absorption bands were studied by Danson et al. (1992) showing that derivative reflectance calculated in the water absorption features minimized the effects due to leaf structure, therefore maximizing the sensitivity to leaf water content. Lately, the broad use of leaf radiative transfer models such as PROSPECT (Jacquemoud & Baret, 1990) for broadleaf species, LIBERTY (Dawson, Curran, & Plummer, 1998) based on radiative transfer characterization in needles, and LEAFMOD (Ganapol, Johnson, Hammer, Hlavka, & Peterson, 1998) among others, enable the simulation of the leaf optical properties as a function of leaf structural and biochemical constituents such as chlorophyll $a+b$ (C_{a+b}), dry matter (C_m), and leaf equivalent water thickness (C_w).

Several research efforts focus on the application of leaf-level indices calculated from water-absorption bands, statistical relationships between leaf reflectance and leaf water content, and *scaling-up* methods to canopy level through radiative transfer simulation. As an example, airborne visible infrared imaging spectrometer (AVIRIS) imagery was used to derive equivalent water thickness in vegetation using nonlinear and linear least squares spectral matching techniques, achieving good agreements with ground measured leaf fuel moisture (LFM) content (Gao & Goetz, 1995). In other studies, Pinzón, Ustin, Castañeda, and Smith (1998) and Ustin et al. (1998) using hierarchical foreground/background analysis (HFBA) showed general success retrieving equivalent water thickness by radiative transfer modeling using the 960-nm absorption band, but breaking down for low LAI canopies due to the increasing effects of soil background and shadows on sparse vegetation. Other ratios, such as the plant water index (PWI, R_{970}/R_{900}) (Peñuelas, Piñol, Ogaya, & Filella, 1997) was used to map vegetation water content with AVIRIS imagery, but found to be affected not only by water content, but also by canopy structure and viewing geometry (Serrano, Ustin, Roberts, Gamon, & Peñuelas, 2000) therefore highly dependent on bi-directional and geometrical effects of the vegetation canopy. The normalized difference water index (NDWI) calculated as $(R_{860}-R_{1240})/(R_{860}+R_{1240})$ was suggested by Gao (1996) in a theoretical study, demonstrating its potential applicability for canopy-level water content estimation based on the liquid water absorption band centered at 1240 nm enhanced by canopy scattering. Nevertheless, Zarco-Tejada and Ustin (2001) showed in a simulation study the dependency of NDWI and the simple ratio water index (SRWI, R_{858}/R_{1240}) on leaf-level variables such as leaf structure and dry matter content, and most importantly, on canopy LAI.

These partially successful results, obtained when estimating vegetation water content, demonstrate the need for modeling efforts to account for leaf and canopy variables and the viewing geometry. Efforts to investigate the successful *scaling up* of optical indices from leaf to canopy level through radiative transfer simulation (Haboudane, Miller, Tremblay, Zarco-Tejada & Dextraze, 2002; Zarco-Tejada, Miller, Mohammed, Noland, & Sampson, 1999; Zarco-Tejada et al., 2001) show the importance of these methods when estimating leaf biochemical constituents from canopy reflectance data. Nevertheless, few investigations are found which apply these radiative transfer methods and model inversion techniques for leaf water content estimation from canopy reflectance imagery. Examples are the simulation studies to estimate equivalent water thickness by model inversion by Jacquemoud, Baret, Andrieu, Danson, and Jaggard (1995), Jacquemoud et al. (1996) and Fourty and Baret (1997) linking the PROSPECT leaf model (Jacquemoud & Baret, 1990) and SAIL canopy model (Verhoef, 1984), showing successful retrievals of C_w from continuous hyperspectral (AVIRIS-simulated) and multispectral (TM-simulated) spectra taking into account leaf- and canopy-level variables. Recently, Ceccato, Flasse, and Grégoire (2002) and Ceccato, Gobron, Flasse, Pinty, and Tarantola (2002) developed an optical index for SPOT-VEGETATION sensor based on global sensitivity analysis using radiative transfer models.

The work presented here investigates the applicability of these radiative transfer techniques to MODIS reflectance data for vegetation water content estimation. A simulation study with synthetic spectra and MODIS-equivalent reflectance is presented, investigating the spectral capabilities of MODIS for estimating leaf equivalent water thickness by inversion of a linked leaf–canopy model. Further, a seasonal field study was undertaken for leaf sampling and analysis of LFM content from 10 study sites, measuring fresh and dry weight of leaf samples. Time-series of MODIS reflectance spectra from the study sites during the period of the field experiment were used for model inversion to estimate equivalent water thickness by radiative transfer simulation.

2. Modeling the effects of water content on MODIS-equivalent reflectance

Willstatter and Stoll (1913) presented the earliest description of a theory to explain the leaf optical properties, with subsequent improvements and development of new leaf models: Allen and Richardson (1968); Breece and Holmes (1971); Woolley (1971); Allen, Gausman, Richardson, and Thomas (1969), Allen, Gayle and Richarson (1970). Allen and Richardson (1968) applied the Kubelka–Munk (K–M) theory (Kubelka & Munk, 1931) to study the interaction of light with stacked plant leaves, relating leaf reflectance and transmittance to leaf scattering and extinction properties of a single compact leaf layer. The *plate model* by Allen et al. (1969) described diffuse reflectance and transmittance of a compact leaf by two parameters: n, refractive index, and k, absorption coefficient, showing improvements upon the K–M formulation. The model, originally developed for a single compact leaf layer, was later extended to multiple layers or *plates* (Allen et al., 1970; Gausman et al., 1970).

Due to its extensive validation, the PROSPECT model (Jacquemoud & Baret, 1990), which is based on this *plate model*, was used in this study to simulate the confounding effects of equivalent water thickness (C_w), dry matter content (C_m), and leaf internal structure (N) on leaf reflectance and transmittance at wavelengths used for leaf water content estimation. As can be seen in Fig. 1 (upper and bottom right plots), optical indices calculated at the liquid water absorption bands centered at 960 and 1150 nm are also affected by dry matter content and leaf internal structure. The effects of such biochemical constituents on indices proposed for estimation of water content from MODIS are studied below, simulating canopy structure, viewing geometry, and incorporating the hotspot effect with the SAILH model (Kuusk, 1985).

2.1. Model simulation at the leaf and canopy levels with water indices

MODIS bands centered at 858 and 1240 nm, with 35 and 20 nm bandwidth, respectively, are used to build the NDWI $[(R_{860}-R_{1240})/(R_{860}+R_{1240})]$ (Gao, 1996), and the SRWI (R_{860}/R_{1240}) (Zarco-Tejada & Ustin, 2001) for vegetation

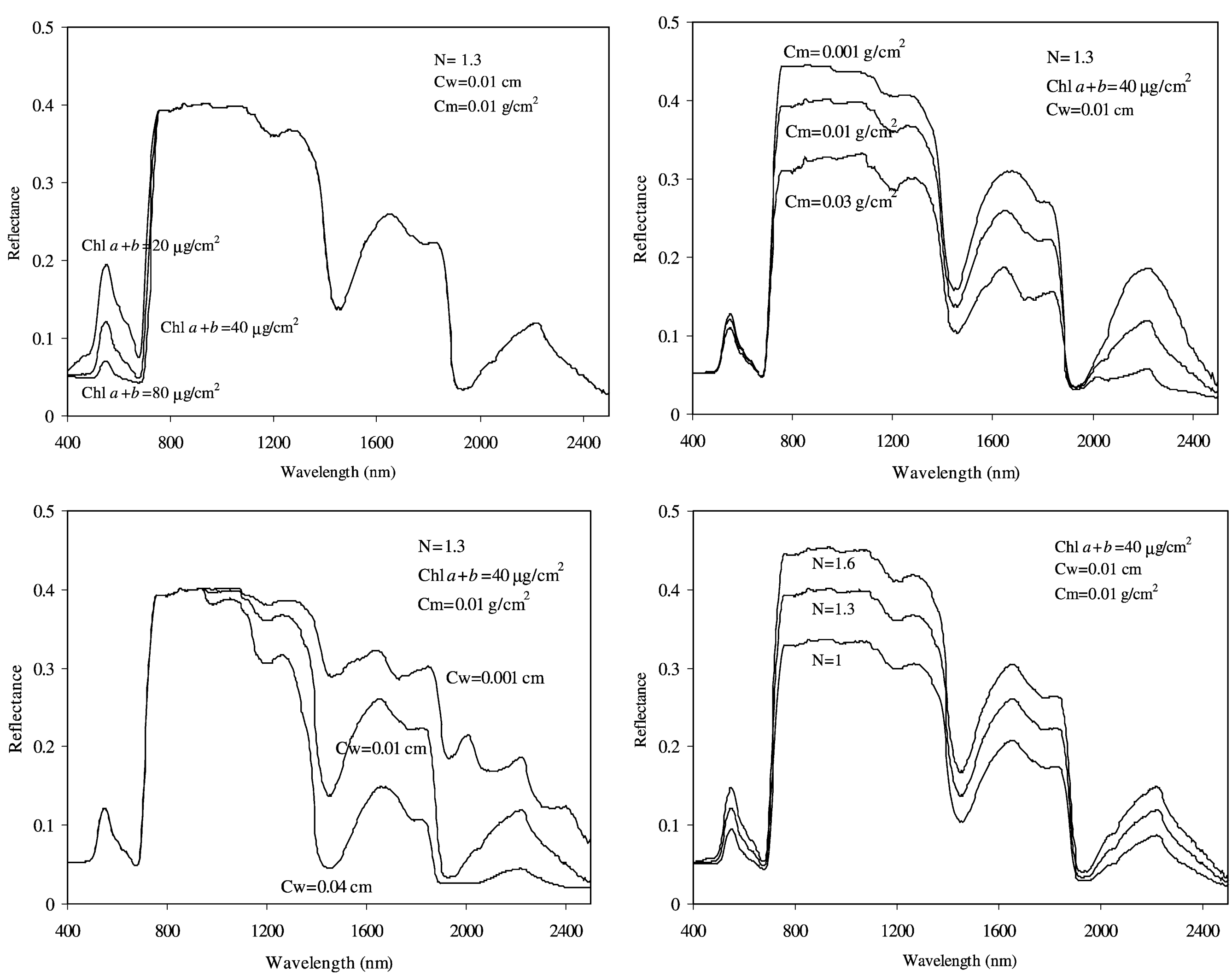

Fig. 1. Effects of leaf biochemical constituents such as chlorophyll C_{a+b} (upper left), dry matter C_m (upper right), equivalent water thickness C_w (lower left), and leaf structural parameter N (lower right) on leaf reflectance, simulated using the PROSPECT model.

water content estimation. The location of MODIS bands R_{1240} on the edge of the liquid water absorption (Fig. 2), and R_{858} used for normalization and insensitive to water content changes (Gao, 1996), make these indices potentially suitable for global monitoring of vegetation water content from MODIS. The effects of atmospheric water vapor and aerosol scattering on R_{858} and R_{1240} MODIS bands were demonstrated by Gao (1996) to cause small perturbations on these reflectance bands for remote estimation of water content.

The SRWI water index was studied through radiative transfer simulation to account for effects due to water content C_w, leaf dry matter C_m, and leaf internal structure N using the PROSPECT leaf model, for a range of values of C_w (in cm) and C_m (in g/cm^2) between 0.001 and 0.03, and N between 0.5 and 2.5 (Fig. 3, top and bottom). It is shown that the primary variables affecting SRWI at the leaf level are C_w and N, with little effect of the C_m constituent on this optical index. The leaf internal structure has a major effect on SRWI at low values (N between 0.5 and 1) with less effect as N increases, but suggesting that both N and C_m leaf variables need to be taken into account for accurate estimates of C_w from SRWI.

At the canopy level, the water index SRWI was simulated to account for canopy structural characteristics such as LAI and the viewing geometry described by sun angle (t_s), view angle (t_v), and relative azimuth angle (p_s). The simulation study illustrates the large effect of LAI on SRWI index calculated from canopy-level simulated reflectance and variable C_w (Fig. 4). The simulation shows that SRWI is highly sensitive to the canopy structural parameter LAI, obtaining a 40% variation when SRWI is modeled with $C_w = 0.03$ cm and LAI changes from 2 to 10, demonstrating the large dependency of water-related optical indices on LAI. For high LAI values, SRWI is still sensitive to changes in leaf water, with index saturation starting after LAI>10 (Fig. 4, bottom). The effects on canopy reflectance and SRWI were studied using high, medium and low values of dry matter C_m and equivalent water thickness C_w through PROSPECT simulations, varying LAI from 2 to 8 in SAILH. Leaf constituents were changed from low to high concentration over their normal range of variation: leaf equivalent water thickness was varied from 0.008 to 0.03 cm, leaf dry matter in the same range [g/cm^2], and using medium values of $C_w = 0.019$ cm and $C_m = 0.019$ g/cm^2

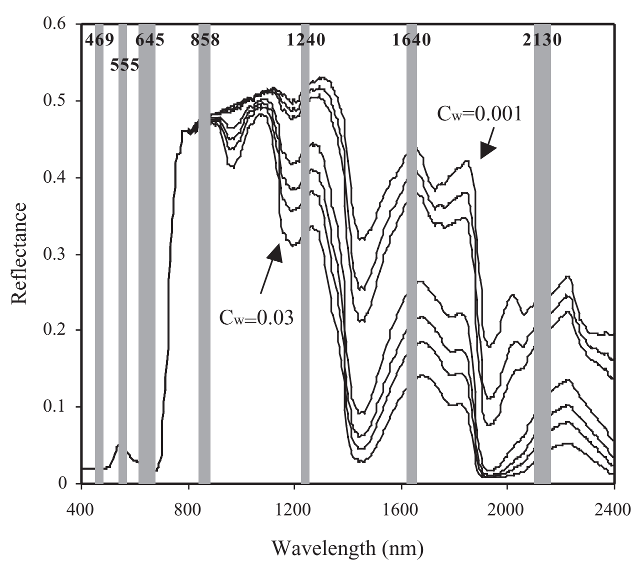

Fig. 2. Modeling canopy-level reflectance using PROSPECT–SAILH models for different values of leaf equivalent water thickness ($C_w = 0.001$–0.03 cm) showing location of MODIS MOD09A1 bands. PROSPECT parameters used were $N = 1.5$, $C_m = 0.019$ g/cm^2, and for SAILH LAI = 5, plagiophile LADF, $t_s = 35°$, $t_v = 0°$, $p_s = 0°$.

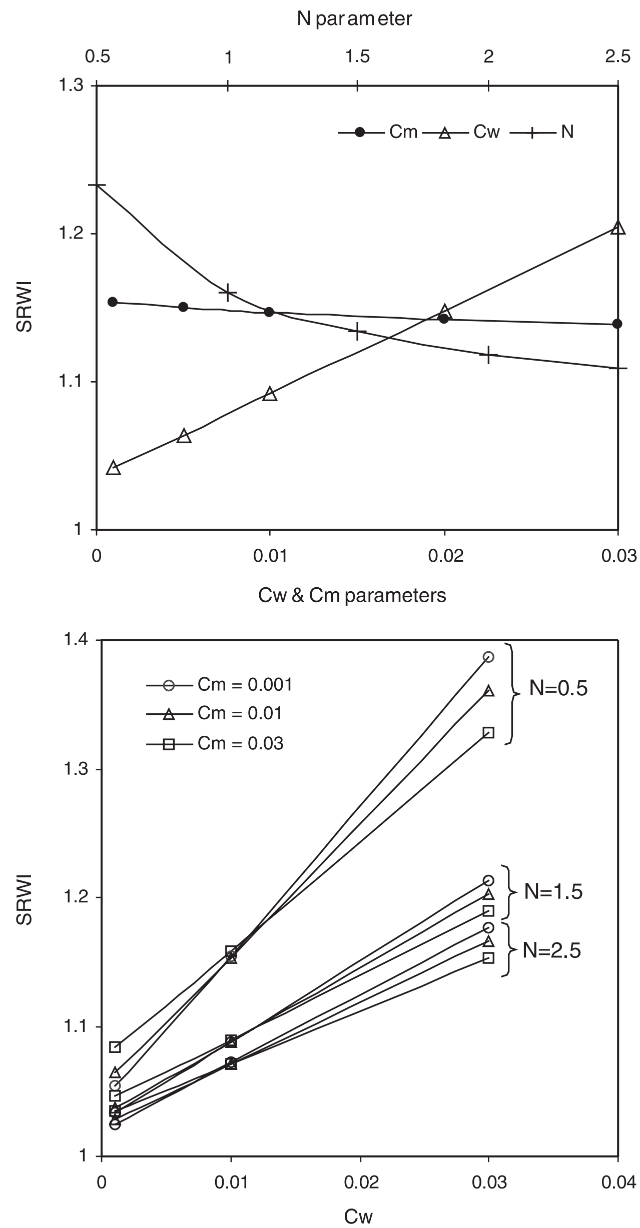

Fig. 3. Modeling SRWI optical index at the leaf level through radiative transfer simulation with the PROSPECT model, using a range of values of water thickness ($C_w = 0.001$–0.03 cm), internal leaf structure ($N = 0.5$–2.5), and leaf dry matter content ($C_m = 0.001$–0.03 g/cm^2).

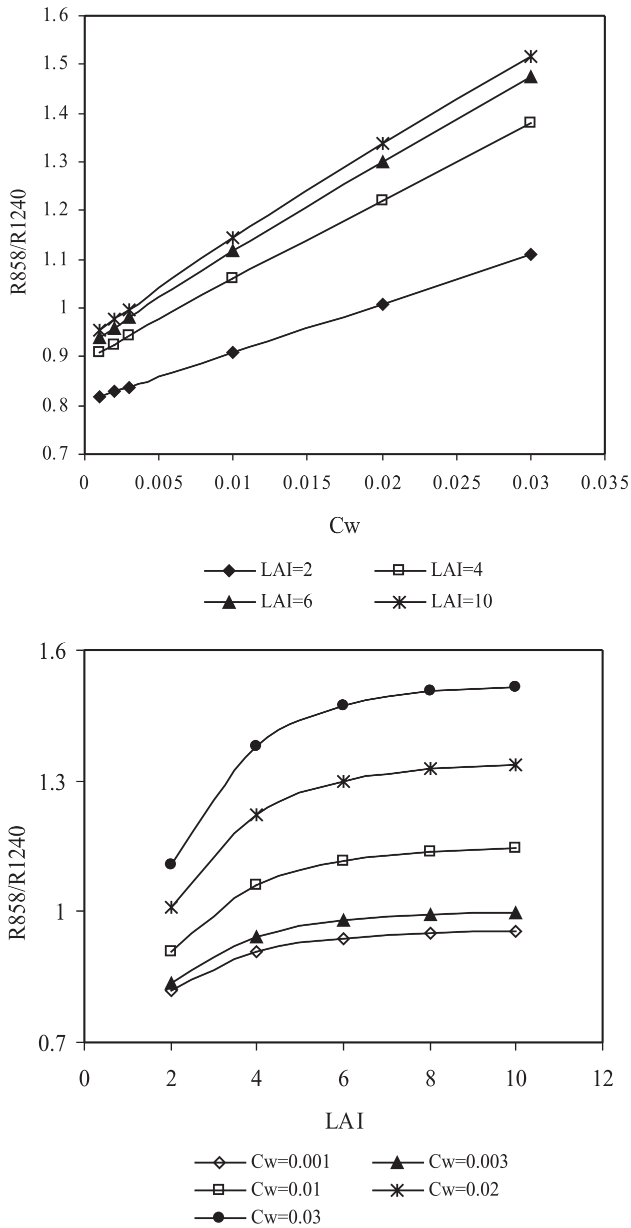

Fig. 4. Modeling the effects of SRWI optical index at the canopy level as a function of LAI, and a range of equivalent water thickness values ranging from $C_w = 0.001$ to $C_w = 0.03$ cm. PROSPECT–SAILH were used for the simulation of leaf and canopy reflectance with other input parameters $C_m = 0.019$ g/cm^2, $N = 1.5$, $C_{a+b} = 50$ μg/cm^2, plagiophile LADF, and viewing geometry $t_s = 30°$, $t_v = 0°$, and $p_s = 0°$.

with LAI = 5 (Fig. 5a,b). For a given set of input parameters, and as demonstrated by leaf-level simulation, changes due to C_m generate a reflectance increment in all bands from

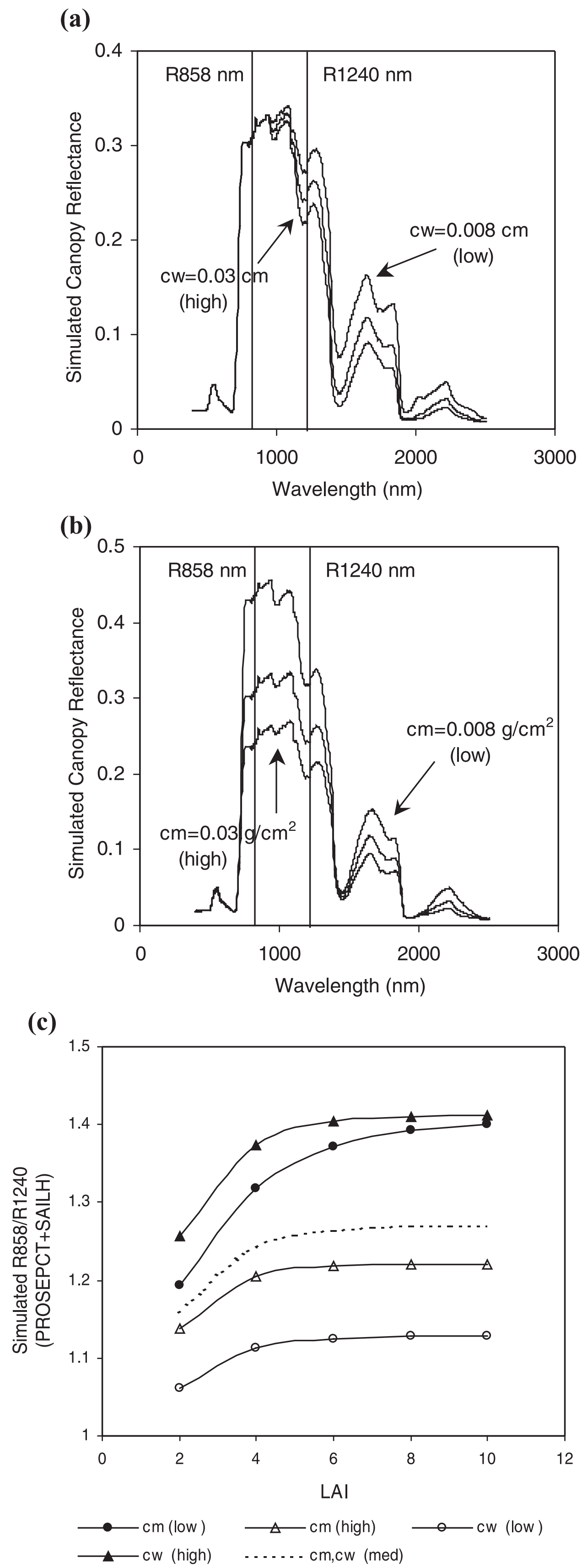

Fig. 5. Simulation of canopy reflectance (a and b) and simulation of SRWI optical index (c) using PROSPECT–SAILH models for high and low values of C_w and C_m (low = 0.008 g/cm^2, high = 0.03 g/cm^2) with normal values of C_m [g/cm^2] and C_w [cm] of 0.019. Other input parameters used in the simulation were $N = 1.5$, $C_{a+b} = 50$ μg/cm^2, plagiophile LADF, and viewing geometry $t_s = 30°$, $t_v = 0°$, and $p_s = 0°$. LAI = 5 was used for top left and right plots.

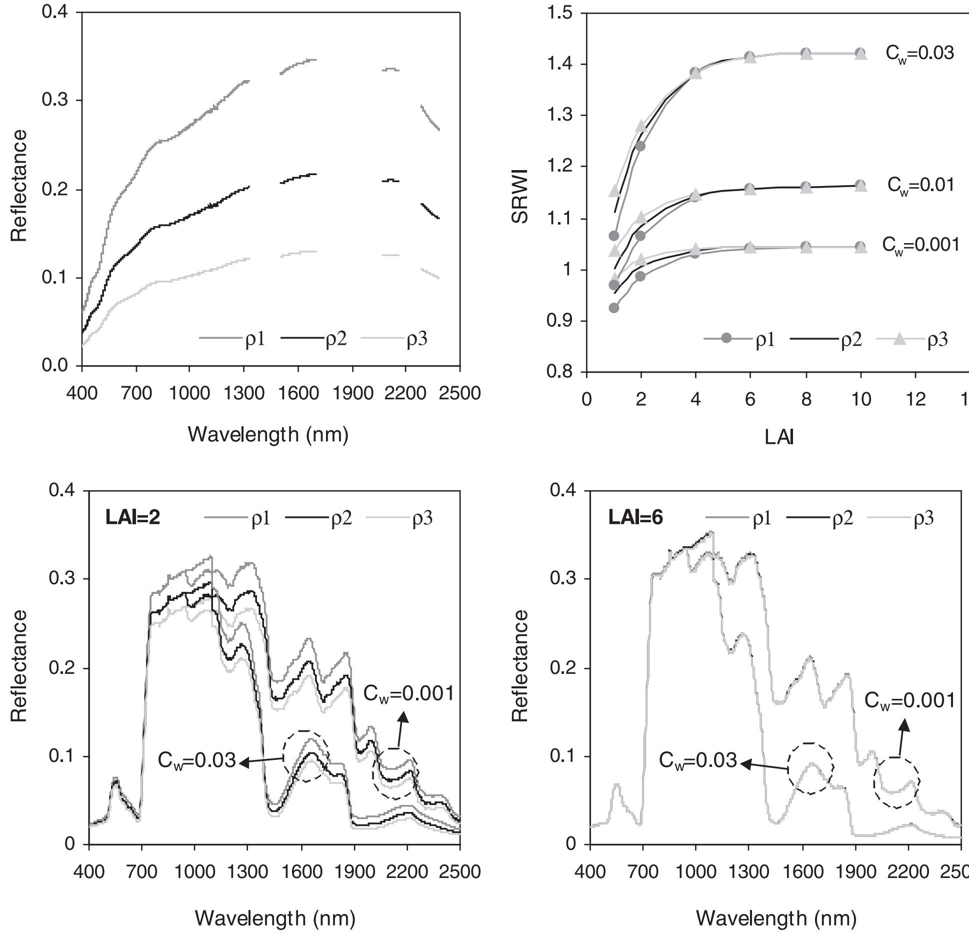

Fig. 6. Soil spectral reflectance in the 400–2500 nm range used as input in the PROSPECT–SAILH linked model (top left). Simulation of SRWI optical index for C_w values ranging from low ($C_w = 0.001$) to high ($C_w = 0.03$) and for an LAI range of 1–10 for each soil background (top right). Canopy reflectance simulation obtained from LAI = 2 (bottom left) and LAI = 6 (bottom right) for C_w ranging from $C_w = 0.001$ to $C_w = 0.03$ and different soil backgrounds.

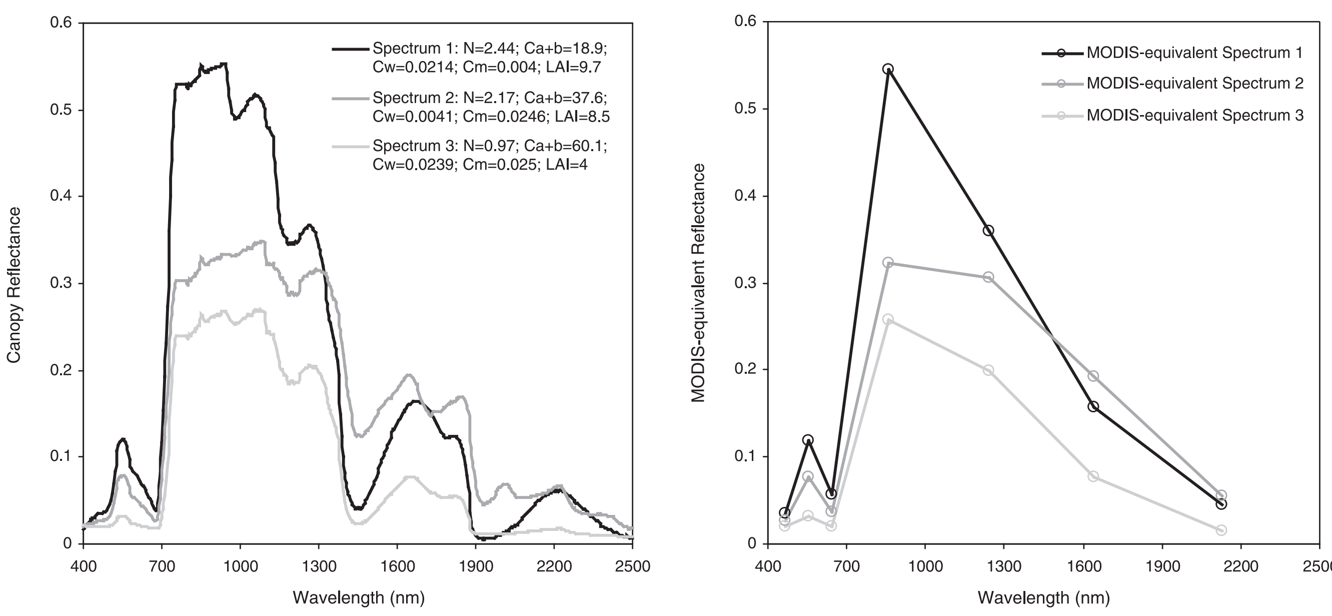

Fig. 7. Example of the synthetic canopy reflectance generated with PROSPECT–SAILH models in the 400–2500 nm range (left), and the MODIS-equivalent reflectance generated using the sensor spectral bandwidth and relative spectral response (right).

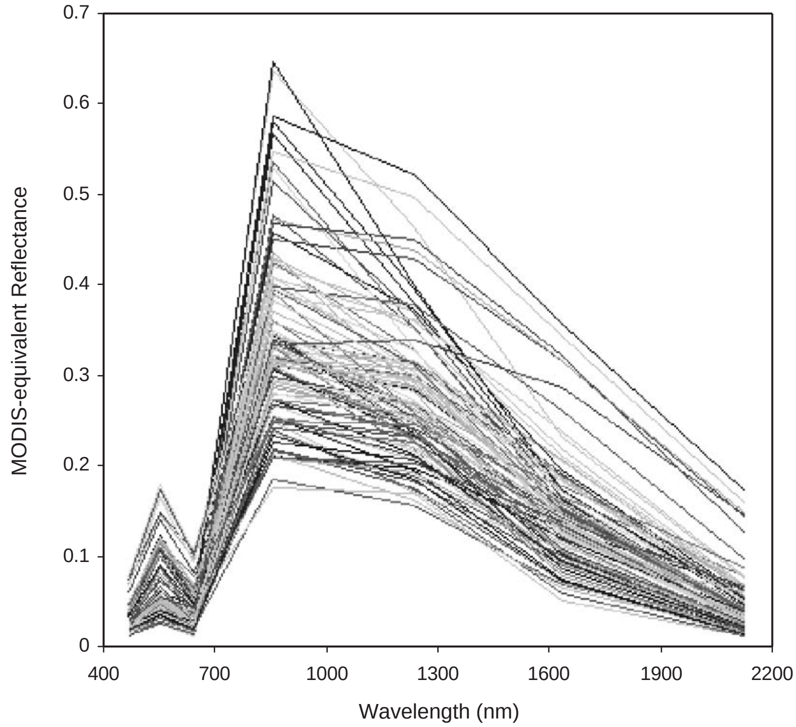

Fig. 8. Set of 100 random MODIS-equivalent synthetic spectra used for model inversion in the simulation study.

R_{858} to R_{1240}, while changes in C_w affect R_{1240} primarily, with R858 insensitive to water content. Variation of SRWI as function of LAI for extreme values of C_m and C_w (Fig. 5c) demonstrate that the index is primarily affected at the canopy level by C_w, with large effects at low LAI ranges (LAI < 5).

The effects of soil reflectance on the SRWI index and on the absolute reflectance were studied with three soil spectra of extreme reflectance values in the 400–2500 nm range (Fig. 6, top left) used as input in the PROSPECT–SAILH linked model. Simulation results obtained for low C_w values ($C_w = 0.001$) to high equivalent water thickness ($C_w = 0.03$) and for an LAI range of 1–10 (Fig. 6, top right) show, as expected, that soil effects on the SRWI optical index are greater at LAI values less than 2. When LAI values are greater than 4, no background effects are found on SRWI for any C_w range, with no effects on the absolute reflectance (Fig. 6, lower left and right). These results suggest that the effects of soil reflectance on canopy reflectance need to be considered when estimating C_w in low LAI canopies, but showing even at such low LAI values that the primary drivers of SRWI variation are LAI and C_w, with less than 10% variation in SRWI for extreme soil values and low LAI (Fig. 6, top right).

These simulation results show that optical indices proposed for water content estimation at the canopy level need appropriate modeling methods to account for leaf- and canopy-level variables. The effects of leaf internal structure,

Table 1
Determination coefficients calculated between the original C_w used for synthetic generation of spectra, and the estimated C_w by inversion for both leaf and canopy levels

	Leaf level (PROSPECT inversion)			Canopy level (PROSPECT–SAILH inversion)			
Variables estimated	C_w	N, C_w, C_m	N, C_{a+b}, C_w, C_m	C_w	N, C_w, C_m	N, C_{a+b}, C_w, C_m, LAI	N, C_w, C_m LAI
Variables known	N, C_{a+b}, C_m	$C_{a+b}=33$ μg/cm^2	None	N, C_{a+b}, C_m, LAI, θ_s, θ_v, ϕ, h, ρ_s	$C_{a+b}=33$ μg/cm^2, LAI, θ_s, θ_v, ϕ, h, ρ_s	θ_s, θ_v, ϕ, h, ρ_s	$C_{a+b}=33$ μg/cm^2, θ_s, θ_v, ϕ, h, ρ_s
Full spectrum (420 bands)	0.99	0.99	0.99	0.99	0.83	0.86	0.67
MODIS bands (7 bands)	0.99	0.91	0.99	0.99	0.80	0.66	0.52
SRWI	0.99	0.95	0.95	0.99	0.67	0.01	0.01
NDWI	0.99	0.95	0.95	0.99	0.67	0.02	0.02

Retrievals were conducted from full spectra, MODIS-equivalent reflectance, and with SRWI and NDWI indices used as merit function. The variables subject to inversion and the variables known and fixed are specified.

leaf constituents C_{a+b}, C_m and C_w on canopy reflectance, soil reflectance effects, and canopy structural characteristics with high effects on the indices, such as LAI, prevent the direct application of SRWI and NDWI on reflectance imagery for accurate mapping of water content. Model inversion methods, which investigate the confounding effects of leaf-level and canopy-level variables on C_w estimation using optical indices SRWI, NDWI, and all land MODIS reflectance bands by inversion techniques, are proposed and studied in the next section.

2.2. Estimation of C_w by model inversion from MODIS-equivalent synthetic spectra

A simulation study was conducted to study the spectral capability of MODIS for retrieving C_w using radiative transfer model inversion methods. Leaf reflectance and transmittance spectra were simulated in the 400–2500 nm spectral range at the MODIS bands using the sensor spectral bandwidth and relative spectral response. One hundred spectra were generated using the PROSPECT model with random leaf parameters within the following ranges: N (0.5–2.5), C_{a+b} (20–80 μg/cm^2), C_w (0.001–0.03 cm) and C_m (0.001–0.03 g/cm^2). The same method was used to generate another set of 100 canopy-level synthetic spectra by the linked PROSPECT–SAILH models, using the same random input leaf parameters, and random canopy structural variable LAI (1–10) and viewing geometry parameters t_s (10–60°), t_v (10–60°), and p_s (0–180°). The leaf angle distribution function was set to plagiophile, and soil reflectance set to a nominal field-measured spectrum (corresponding to ρ_2 in Fig. 6, top left). The hotspot effect incorporated in SAILH (Kuusk, 1985) takes into account the leaf size and the associated shadowing effects on the bidirectional reflectance, calculating the hotspot parameter as the ratio of the leaf size to the canopy height (s/l). Datasets were perturbed with 2.5% relative Gaussian noise prior to inversion. Fig. 7 shows examples of the synthetic canopy reflectance randomly generated with PROSPECT–SAILH models in the 400–2500 nm range (Fig. 7, left), the MODIS-equivalent reflectance generated using the sensor spectral bandwidth and relative spectral response (Fig. 7, right). Illustrated in Fig. 8 is the random set of 100 canopy-level MODIS-equivalent synthetic spectra used for model inversion in this simulation study.

The sets of 100 leaf and 100 canopy-level synthetic spectra were used as inputs for the model inversion to estimate the leaf parameters that generated the original spectra, and the retrieval capabilities of C_w assessed under different assumptions. In this method of inverting a canopy reflectance model coupled with a leaf model (Demarez & Gastellu-Etchegorry, 2000; Jacquemoud, 1993; Jacquemoud, Bacour, Poilve, & Frangi, 2000; Jacquemoud et al., 1995, Kuusk, 1998; Zarco-Tejada et al., 2001), the leaf radiative transfer simulation uses leaf biochemical constituents as inputs to model leaf reflectance and transmittance that are, in turn, used as input for the canopy reflectance model. Error calculation consists of determining by exhaustive iteration the set of parameters P=(N, C_{a+b}, C_w, C_m, LAI, t_s, t_v, p_s,...) which minimize the merit function Δ^2 within their given range of operation (Eq. (1)).

$$\Delta^2 = \sum_n [r_m(\lambda_i) - r^*(\lambda_i, P)]^2 \qquad (1)$$

where $r_m(\lambda_i)$ is the measured or synthetic canopy spectral reflectance; $r^*(\lambda_i,P)$ is the modeled canopy spectral reflectance with a set of P parameters;

Different strategies are used to build the merit function Δ^2 used for minimizing the error between the measured or synthetic and the simulated canopy reflectance, as discussed in Zarco-Tejada et al. (2001). In the present study, two

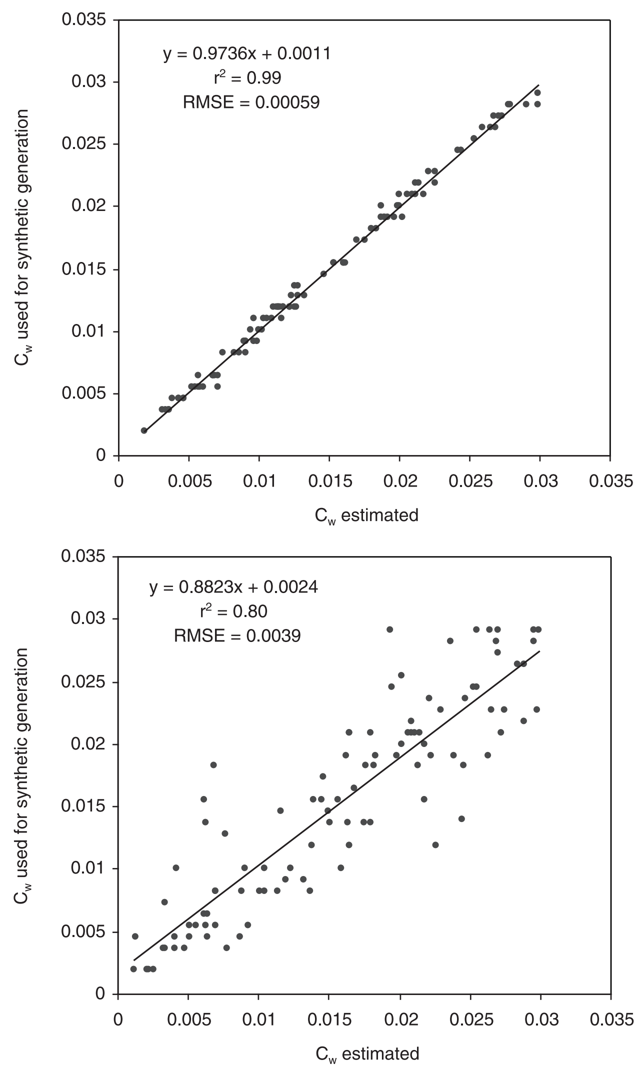

Fig. 9. Determination coefficients and RMSE obtained between original C_w used for random synthetic generation, and the estimated C_w by inversion techniques for leaf (top) and canopy (bottom) levels with MODIS-equivalent reflectance. At the leaf level, the PROSPECT model was used with N, C_{a+b}, C_w, and C_m variables subject to inversion (top). At the canopy level, the PROSPECT–SAILH linked model was used with N, C_m, and C_w inverted, C_{a+b} fixed, and LAI known (bottom).

methods are used to build the merit function: (i) using all available reflectance bands in the 400–2500 nm spectral region, therefore comparing the estimated with the measured reflectance and computing the error using all spectral bands (Jacquemoud, 1993; Jacquemoud et al., 1995, 2000); and (ii) building merit functions based on spectral transforms for inversion (Zarco-Tejada et al., 2001) and *scaling-up* approaches (Haboudane et al., 2002) based on optical indices or combinations of indices related to the leaf variable subject to estimation (NDWI, SRWI for C_w estimation in this case). The latter approach of building merit functions with optical indices generally relies on the error calculation based on single reflectance ratio values only, rather than on the entire spectrum. Advantages of using optical indices in the merit function are because specific optical indices (i) maximize the sensitivity to the leaf biochemical constituent while minimizing other leaf or canopy variables (Haboudane et al., 2002); and (ii) normalize external effects due to atmosphere, illumination conditions, and viewing geometry. The disadvantages of merit functions built on indices are related to the loss of spectral information when data are based on a few bands rather than on the entire reflectance spectrum.

In this simulation study, the estimation of C_w by model inversion was carried out at leaf and canopy levels from original synthetic full spectra, from MODIS-equivalent reflectance calculated from the full spectrum using the sensor spectral response function, and building merit functions with

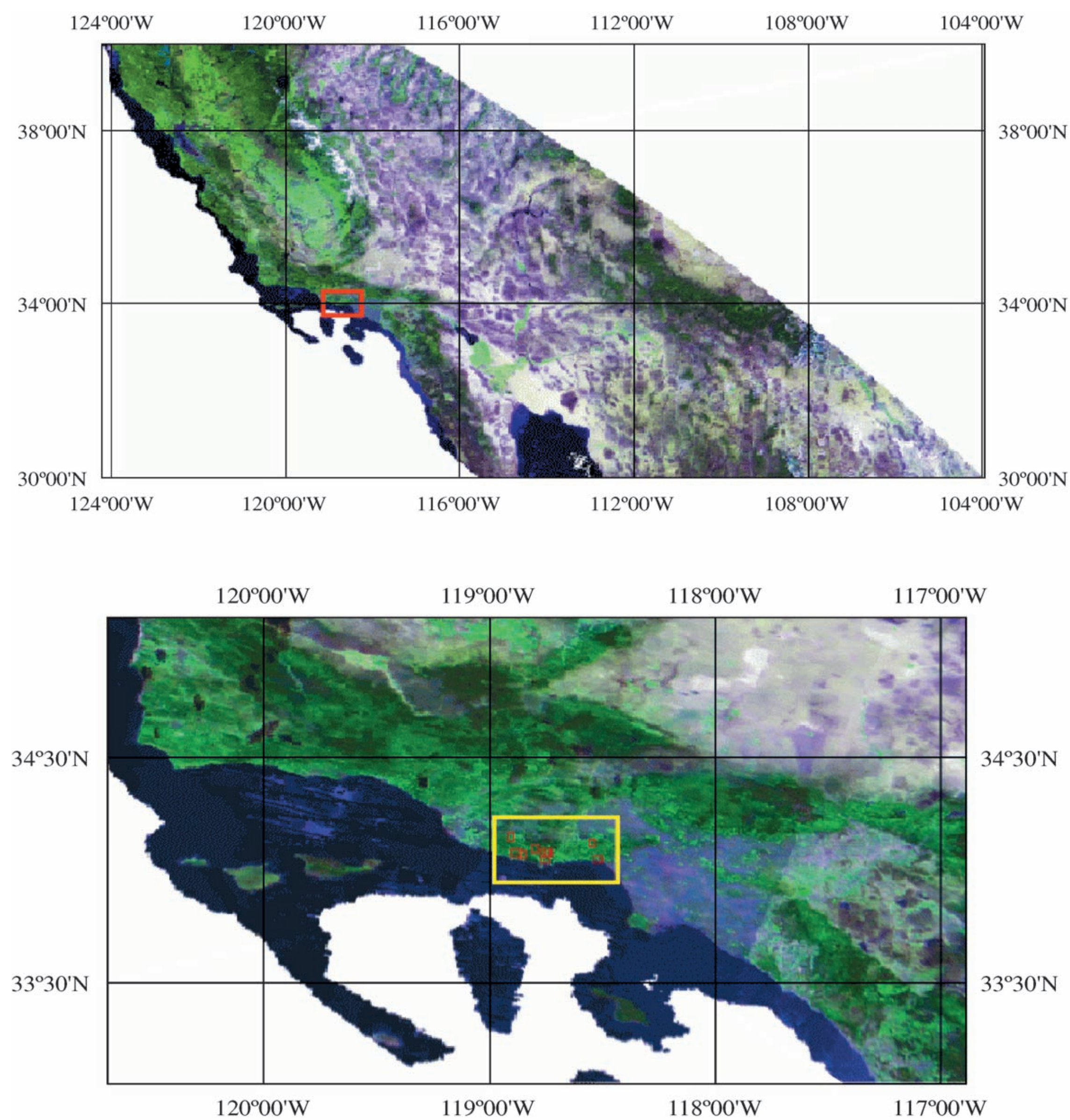

Fig. 10. Study area in California, USA, used for the field sampling campaign and biochemical analysis of leaf water content from 10 sites between March and September 2000. MODIS MOD09A1 reflectance image composite with 555 nm (blue), 645 nm (red), and 858.5 nm (green) reflectance bands.

the SRWI and NDWI optical indices. Different combinations of leaf- and canopy-level variables kept fixed and subject to inversion were used to study the retrieval capacity as function of the number of guessed variables both at leaf and canopy levels. Therefore, the objective was to study, using synthetic spectra, whether MODIS reflectance bands are capable of estimating C_w given the confounding effects of leaf and canopy parameters previously described. Moreover, the applicability of SRWI and NDWI optical indices as merit functions for C_w estimation was also studied.

Results of the simulation study are shown in Table 1, where determination coefficients calculated between C_w used for synthetic spectra generation, and the C_w estimated by inversion are shown for both leaf and canopy levels. The table also shows the set of variables kept fixed and estimated at both leaf and canopy levels. At the leaf level, results using only the PROSPECT model and four variables subject to inversion (N, C_{a+b}, C_w, and C_m), show that C_w can be estimated using the full spectrum (as previously demonstrated by Jacquemoud et al., 1996) and also using

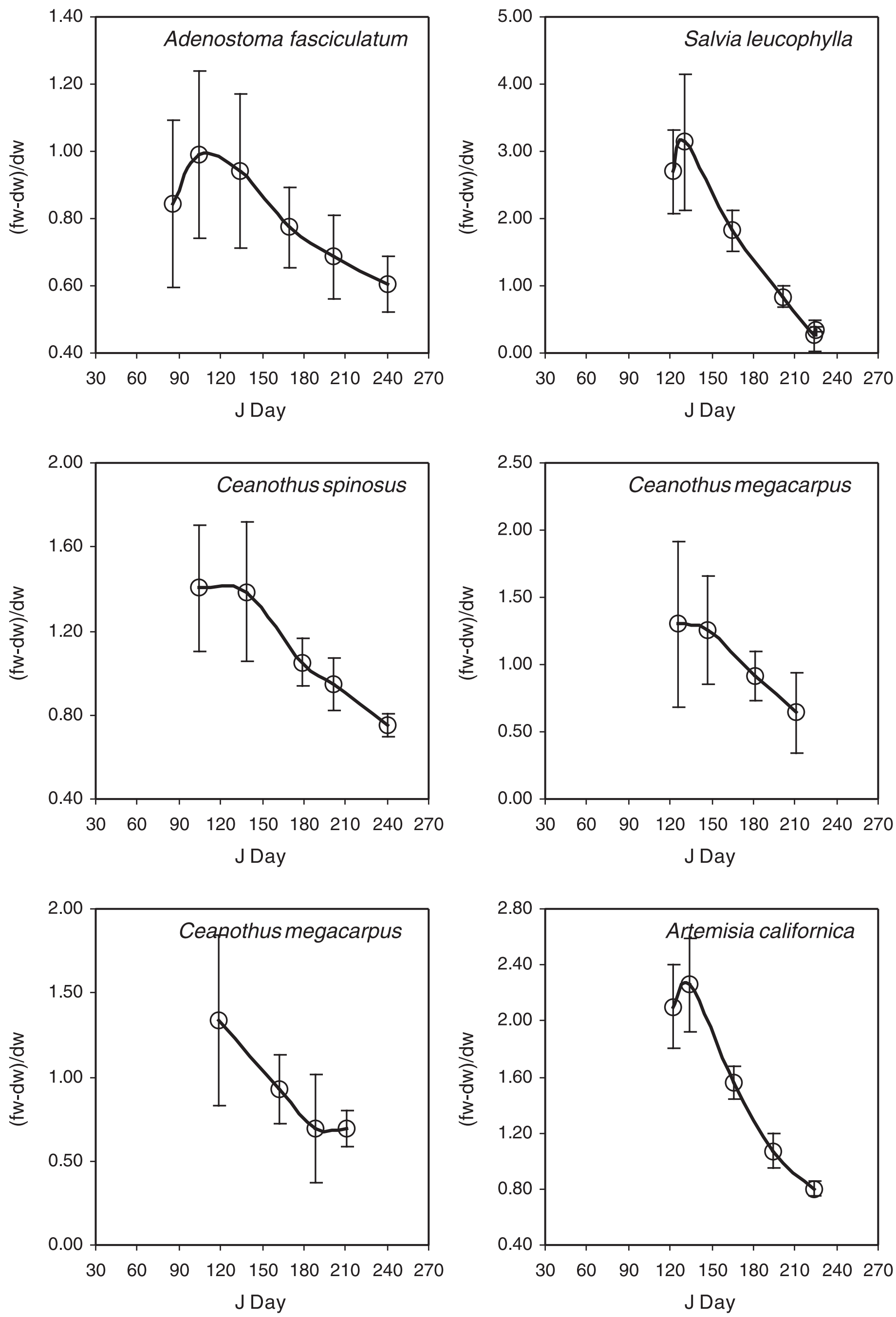

Fig. 11. LFM calculated as (fw − dw)/dw measured at selected study sites where leaf sampling was carried out from March until September 2000, showing the variation of leaf water content over time.

the seven MODIS bands ($r^2 = 0.9$ in all cases) even when all four leaf variables are subject to inversion. These simulation results demonstrate that MODIS bands are placed in spectral regions capable of determining C_w when four leaf variables N, C_{a+b}, C_w, and C_m are unknown (Fig. 9, top). When pigment content is set to a fixed value ($C_{a+b} = 33$ μg/cm^2 in this case)—hence guessing only N, C_w, and C_m, the determination coefficient obtained is $r^2 = 0.91$ when estimating C_w from MODIS bands, and $r^2 = 0.99$ from the full spectrum. Moreover, when the optical indices SRWI and NDWI are used as merit functions, with no other spectral information than R_{858} and R_{1240} nm reflectance bands in the function built for error calculation, results also demonstrate that C_w can be properly estimated when all four leaf variables are subject to inversion ($r^2 = 0.95$).

At the canopy level study with synthetic spectra, the four leaf variables N, C_{a+b}, C_w, and C_m were subject to inversion along with additional variables such as LAI, and viewing geometry t_s, t_v, and p_s. When C_w is the only variable subject to estimation, determination coefficients are $r^2 = 0.99$ in all four cases (from full spectrum, MODIS bands, SRWI, and NDWI). MODIS bands are capable of estimating C_w when the three leaf parameters—N, C_w, and C_m—are subject to inversion, C_{a+b} is set to a fixed value, and LAI and viewing geometry are known ($r^2 = 0.83$ for full spectrum, and $r^2 = 0.80$ for MODIS-equivalent data). When the four leaf variables—N, C_{a+b}, C_w, and C_m—and the canopy LAI are inverted, determination coefficients for the full spectra is $r^2 = 0.86$; $r^2 = 0.66$ is obtained for MODIS-equivalent data, demonstrating, as expected, that inverting five variables with seven MODIS bands obtains worse results than when using the full spectrum. When C_{a+b} is set to a fixed value and N, C_w, C_m, and LAI are estimated, results are $r^2 = 0.67$ from the full spectrum, and $r^2 = 0.52$ from the MODIS-equivalent reflectance. These results demonstrate that MODIS data can be used to estimate C_w from canopy-level reflectance, obtaining $r^2 = 0.99$ if all other variables are known (N, C_{a+b}, C_m, LAI); $r^2 = 0.80$ if N, C_m, and C_w are inverted, C_{a+b} is fixed and LAI is known (Fig. 9, bottom); $r^2 = 0.66$ if N, C_{a+b}, C_w, C_m, and LAI are estimated; and $r^2 = 0.52$ if N, C_w, C_m and LAI are estimated, with C_{a+b} fixed (Table 1).

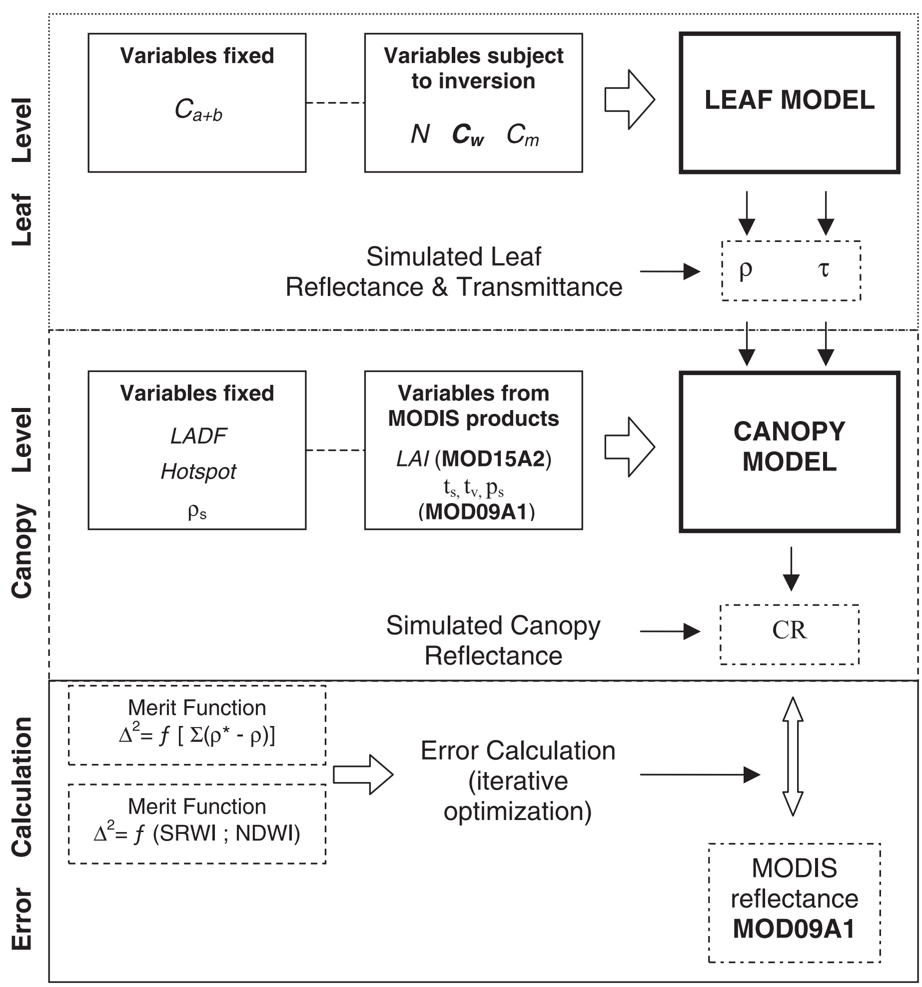

Fig. 12. Schematic view of the link between leaf and canopy models for leaf equivalent thickness (C_w) estimation by model inversion. The iterative method consisted on building a merit function with (i) optical indices SRWI and NDWI; (ii) with all MODIS MOD09A1 reflectance bands.

The use of SRWI and NDWI indices as the only components of the merit function fails at canopy level if more than three variables are subject to inversion, but $r^2=0.67$ is obtained if N, C_w, and C_m are estimated, C_{a+b} is fixed, and LAI is known (for this same set of variables, r^2 was 0.80 when all MODIS bands are used). The results of this simulation study with synthetic MODIS-equivalent reflectance demonstrate the theoretical capability of MODIS to estimate C_w by model inversion of coupled leaf and canopy radiative transfer models. This approach is used in the next section, where the model inversion method is applied to real MODIS reflectance data and the results are compared with field-measured water content measurements.

3. Field sampling study and results for C_w estimation from MODIS data

A field sampling campaign was conducted for the analysis of LFM content, measuring fresh and dry weight from leaf samples collected in 10 study sites of chaparral vegetation in California (USA) between March and September, 2000. Data collection was conducted as part of research to study spatially explicit models of fire spread through chaparral fuels (Morais, 2001). MODIS reflectance data were obtained for the same period of field data acquisition, and inversion methods conducted linking PROSPECT leaf model with the SAILH canopy reflectance model. Description of the leaf sampling scheme and satellite data used in this study is given below.

3.1. Ground measurements of leaf water content

A total of 10 study sites were sampled between March and September 2000, from which 560 leaf samples were collected for measurement of water content at intervals of 3–4 weeks. Chaparral species sampled were *Adenostoma fasciculatum*, *Adenostoma sparsifolium*, *Artemisia californica*, *Ceanothus megacarpus*, *Ceanothus spinosus*, *Salvia leucophylla*, and *Salvia mellifera* located within the area −118.913° (longitude), 34.1523° (latitude) and −118.5619° (longitude), 34.0496° (latitude) in California, USA (Fig. 10).

Study sites were selected at random within the area of homogeneous chaparral vegetation. Twelve branchwood samples with foliage were clipped from new growth and old growth at each site. Leaf samples were placed in separate sampling containers, with the mass of each empty container recorded previously. Samples were collected between 11:00 and 15:00 h, placed in ice for transport to the laboratory and weighted to obtain the fresh weight [fw]. Containers were measured in the laboratory after collection, and samples placed in a pre-heated oven at 40 °C until a stable dry weight [dw] was reached. Dried samples in containers were sealed and re-weighted to obtain dry weight per sample (as described in Morais, 2001). LFM was calculated from all study sites as [(fw − dw)/dw] to monitor leaf water content variation over time, as explained by Burgan (1996) and Chuvieco, Deshayes, Stach, Cocero, and Riaño (1999). The relationship between LFM and equivalent water thickness is discussed in Ceccato et al. (2001), who studied the potential for remote estimation of leaf water content from reflectance data. Previous results by Gao and Goetz (1995) showed a relationship between reflectance-derived equivalent water thickness and leaf moisture content, obtaining a good agreement of $R=0.78$ using hyperspectral data. Fig. 11 shows the time series of LFM at the MODIS study sites where leaf samples were measured, demonstrating the variation of leaf water content within the period of field sampling.

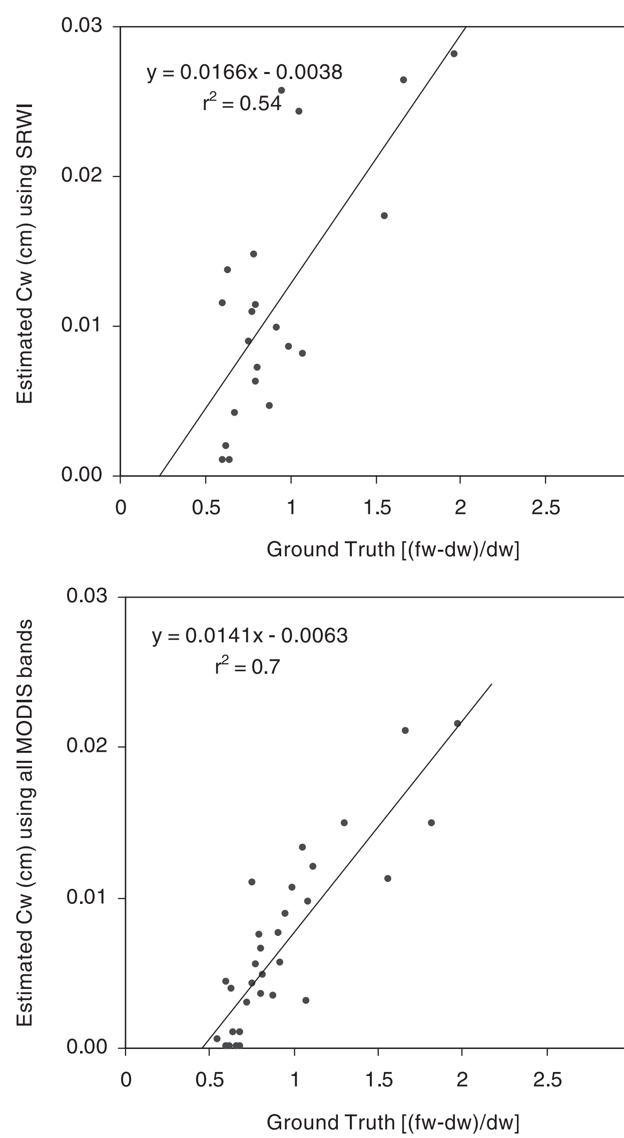

Fig. 13. Relationships achieved between ground truth LFM [(fw − dw)/dw] measured in all study sites and C_w estimated by model inversion from MODIS reflectance using SRWI for the merit function (top) and all MOD09A1 reflectance bands (bottom) for the period June–September 2000.

3.2. MODIS data used for estimates of leaf water content

MODIS surface reflectance product MOD09A1 (500 m spatial resolution) and LAI product MOD15A2 (1 km spatial resolution) were used for C_w estimation during the period June to September 2000. These MODIS reflectance images are 8-day composites of the surface spectral reflectance for each band at 469 nm (20 nm bandwidth), 555 nm (20 nm), 645 nm (50 nm), 858.5 nm (35 nm), 1240 nm (20 nm), 1640 nm (24 nm), and 2130 nm (50 nm). Compensation for the effects of atmospheric gases, aerosols, and thin cirrus clouds is applied to all non-cloudy MOD35 Level 1B pixels (Parkinson & Greenstone, 2000; Strahler & Muller, 1999). The product uses input from bidirectional reflectance distribution function (BRDF)/Albedo product (MOD43), atmospheric profiles (MOD07) for ozone, total precipitable water (MOD05) for water vapor, aerosol product (MOD04) for aerosols, and MODIS band 26 for cirrus clouds. The MODIS LAI product is an 8-day composite derived from the atmospherically corrected surface reflectance product MOD09, land cover product MOD12, and ancillary information on surface characteristics using a 3D radiative transfer model.

MODIS reflectance (MOD09A1) and LAI (MOD15A2) data were reprojected from Integerized Sinusoidal ISIN to geographic projection. LAI (from MOD15A2 product), and reflectance, viewing geometry parameters sun angle (t_s), view angle (t_v), and relative azimuth angle (p_s) (from MOD09A1 product) were extracted for every pixel in the composited reflectance image, since each pixel in the image is collected under different viewing geometry characteristics, orbit and day within the 8-day period. The range of variation for the viewing geometry of all MODIS reflectance spectra used in this study was 11–38° for t_s, 10–61° for t_v, and −24° to 138° for p_s.

The time series of MODIS reflectance data were used for inversion in the linked leaf–canopy reflectance model as described in the previous sections. The iterative technique consisted of building the merit function with the SRWI optical index, as well as using all MODIS MOD09A1 reflectance bands, with viewing geometry (t_s, t_v, and p_s)

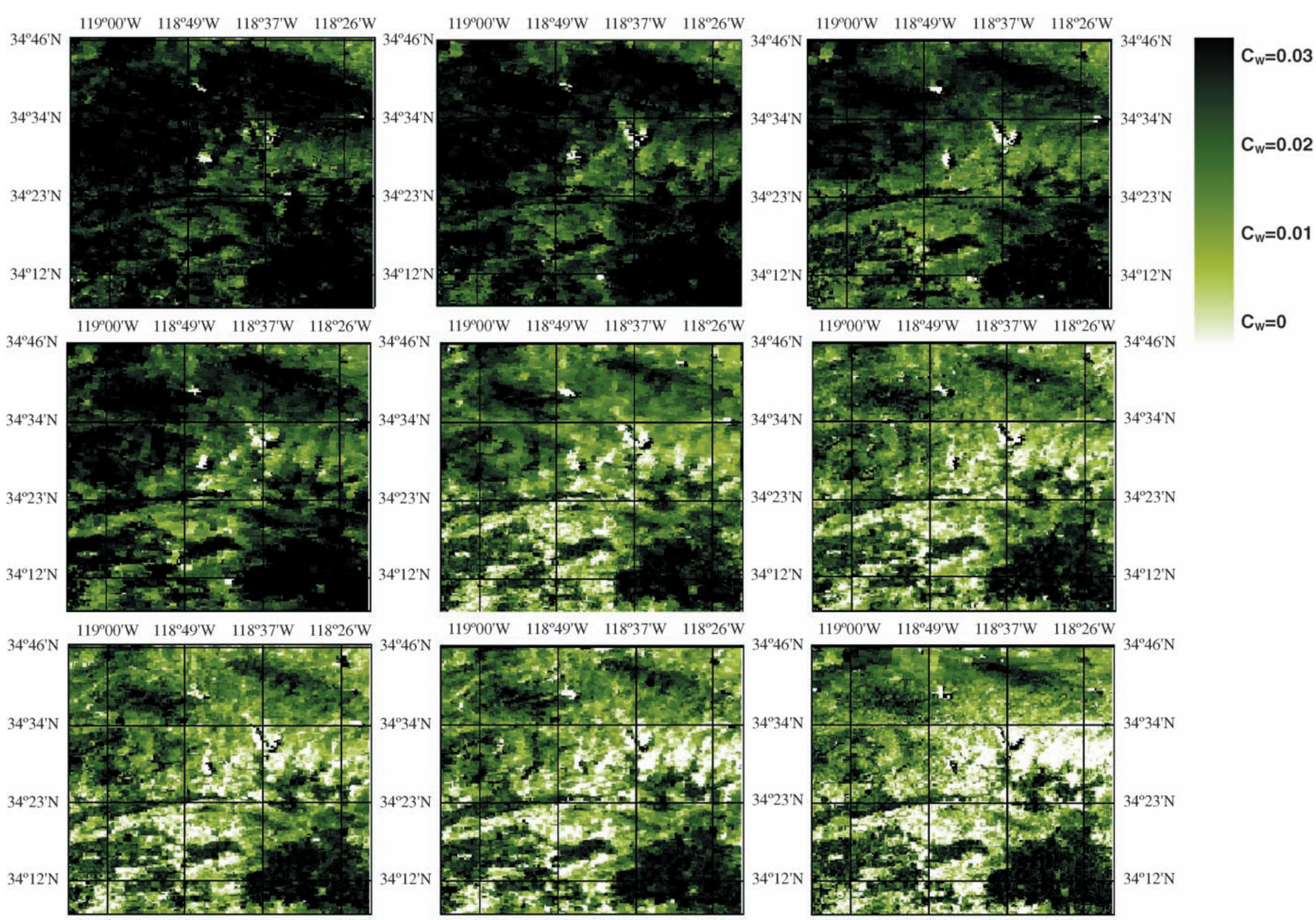

Fig. 14. Time series of MODIS-estimated leaf C_w in the study region of chaparral vegetation within boundaries −118.913° (longitude), 34.1523° (latitude) and −118.5619° (longitude), 34.0496° (latitude) used for ground truth data collection for the period June–September 2000. Reflectance and viewing geometry (t_s, t_v, p_s) from MOD09A1, and LAI from MOD15A2 MODIS products were used as input parameters in the iteration method, with N, C_w and C_m leaf parameters subject to inversion. MODIS images from the study area correspond to Julian days 161, 169, 185, 201, 233, 241, 249, 265, and 273, of year 2000. Darker green color corresponds to higher C_w.

and LAI from the MODIS products (Fig. 12). Variables subject to inversion were the leaf structural parameter N, leaf dry matter C_m, and leaf equivalent water thickness C_w, with variables set to constant values in the inversion procedure $C_{a+b} = 33$ μg/cm^2, plagiophile LADF, and soil spectral reflectance measured in the field.

3.3. Results of the model inversion for leaf water content estimation from MODIS

Estimation of leaf C_w by iteration (Fig. 12) was compared with ground-measured water content from each study site using the MODIS data coinciding with dates used for leaf sampling. Results obtained from comparing the estimated C_w by radiative transfer model inversion with the field-measured LFM content (Fig. 13) demonstrated the capability of MODIS reflectance data to track changes of water content in vegetation. C_w estimated using SRWI index as merit function achieved $r^2 = 0.54$ (Fig. 13, top), obtaining better results $r^2 = 0.7$ (Fig. 13, bottom) when all MODIS bands are used in the model inversion, consistent with the simulation results presented in previous sections.

These results were further analyzed to study the relationship of the estimated C_w with a potential canopy LAI variation over the period of this study. The objective was to demonstrate that C_w estimated by inversion from MODIS was independent and not driven by LAI seasonal changes that occurred at the study sites over the period of the study. The relationship between the LAI input parameter in the model inversions (MOD15A2) and the model-estimated leaf C_w was $r^2 = 0.12$, where $r^2 = 0.1$ is obtained between LAI and ground measured relative leaf water content in all sites between June and September 2000. These results suggest that seasonal estimates of leaf water content can be conducted by radiative transfer modeling from MODIS reflectance bands using inversion techniques. The same methods were applied pixel by pixel to MODIS images, mapping C_w by model inversion (Fig. 14). It shows the MODIS-estimated leaf equivalent water thickness for the period June–September 2000 over the study region of chaparral vegetation used in this study, illustrating the changes in water content occurred over the time period.

4. Conclusion

Simulation methods and results from the modeling and field studies described in this article demonstrate that leaf water content can be globally monitored with MODIS reflectance data by radiative transfer modeling. Optical indices previously suggested in the literature as potential indicators of vegetation water content, such as SRWI and NDWI, were used in a simulation study with linked leaf–canopy models. Leaf- and canopy-level variables such as leaf structure, dry matter content, soil reflectance, LAI, and the viewing geometry were studied through model simulation to account for their effects on the optical indices built from R858 and R1240 MODIS bands. Modeling analysis demonstrates that SRWI and NDWI are highly sensitive to LAI, with more effects of low LAI on the index as C_w increases. For high LAI values, the SRWI index is still sensitive to changes in leaf equivalent water thickness, with saturation starting at LAI greater than 10. These results are consistent with previous studies that indicate the need for modeling methods to account for leaf- and canopy-level effects on the optical indices, especially LAI, therefore preventing the application of such indices directly on the imagery for biochemical constituent estimation of C_w.

Synthetic spectra were generated in two simulation studies at leaf and canopy levels using continuous reflectance and MODIS-equivalent data to study the capability of MODIS bands to successfully retrieve C_w by inversion. Inversion methods both at the leaf and canopy levels demonstrated that C_w could be successfully estimated by the seven MOD09A1 MODIS bands when leaf variables N, C_w, and C_m are subject to inversion by iteration. The SRWI and NDWI indices used as a merit function successfully retrieved C_w by inversion when three leaf variables are subject to inversion, but failed when more than three variables are simultaneously estimated.

Model inversion methods proposed here for C_w estimation by linking leaf and canopy models were confirmed using MODIS reflectance and ground data of LFM content measurements collected between March and September 2000 from 10 study sites of chaparral vegetation in California, USA. MODIS reflectance, viewing geometry t_s, t_v, p_s, and LAI were used as inputs for the minimization procedure in the model inversion. Radiative transfer inversion methods conducted in the study consisted on using SRWI as merit function, and using all MOD09A1 MODIS reflectance bands, with leaf N, C_w and C_m subject to estimation. Successful results were found when comparing MODIS-estimated C_w with ground truth LFM (fw − dw)/dw from the study sites, obtaining $r^2 = 0.54$ when SRWI is used in the merit function, and $r^2 = 0.7$ when MOD09A1 MODIS bands are used for model inversion.

This simulation and field study results suggest the potential use of a linked leaf–canopy radiative transfer approach for global monitoring of leaf water content from MODIS reflectance and inversion methods.

Acknowledgements

This work was supported by NASA contract NAG5-9360 *Incorporating New EOS Data Products into Models to Improve Estimates of Biogeochemical Processes*. The authors gratefully acknowledge M. Marais and D. Roberts (University of California, Santa Barbara) and C. Lee (California State University, Long Beach) for their contribution in the leaf data used in this study. W. Verhoef and S. Jacquemoud are gratefully acknowledged for providing computer code for leaf and canopy reflectance models; B.-C. Gao for contributing water vapor transmittance simulation data; and E. Vera-Toscano for reviewing the manuscript. The authors thank the anonymous reviewers for very valuable suggestions and criticism.

References

Aldakheel, Y. Y., & Danson, F. M. (1997). Spectral reflectance of dehydrating leaves: measurements and modeling. *Int. J. Remote Sens.*, *18*, 3683–3690.

Allen, W. A., Gausman, H. W., Richardson, A. J., & Cardenas, R. (1971). Water and air changes in grapefruit, corn and cotton leaves with maturation. *Agron. J.*, *63*, 392–394.

Allen, W. A., Gausman, H. W., Richarson, A. J., & Thomas, J. R. (1969). Interaction of isotropic light with compact plan leaf. *J. Opt. Soc. Am.*, *59*(10), 1376–1379.

Allen, W. A., Gayle, T. V., & Richarson, A. J. (1970). Plant canopy irradiance specified by the Duntley equations. *J. Opt. Soc. Am.*, *60*(3), 372–376.

Allen, W. A., & Richardson, A. J. (1968). Interaction of light with a plant canopy. *J. Opt. Soc. Am.*, *58*, 1023–1028.

Belanger, M. J., Miller, J. R., & Boyer, M. G. (1995). Comparative relationships between some red edge parameters and seasonal leaf chlorophyll concentrations. *Can. J. Remote Sens.*, *21*, 16–21.

Breece, H. T., & Holmes, R. A. (1971). Bidirectional scattering characteristics of healthy green soybean and corn leaves vivo. *Appl. Opt.*, *10*, 119–127.

Burgan, R. E. (1996). Use of remotely sensed data for fire danger estimation. *EARSeL Adv. Remote Sens.*, *4*(4), 1–8.

Carter, G. A. (1991). Primary and secondary effects of water content of the spectral reflectance of leaves. *Am. J. Bot.*, *78*, 916–924.

Carter, G. A. (1993). Responses of leaf spectral reflectance to plant stress. *Am. J. Bot.*, *80*, 239–243.

Carter, G. A. (1994). Ratios of leaf reflectances in narrow wavebands as indicators of plant stress. *Int. J. Remote Sens.*, *15*, 697–704.

Ceccato, P., Flasse, S., & Grégoire, J. M. (2002). Designing a spectral index to estimate vegetation water content from remote sensing data: Part 2. Validation and applications. *Remote Sens. Environ.*, *82*, 198–207.

Ceccato, P., Flasse, S., Tarantola, S., Jacquemoud, S., & Gregoire, J. M. (2001). Detecting vegetation leaf water content using reflectance in the optical domain. *Remote Sens. Environ.*, *77*, 22–33.

Ceccato, P., Gobron, N., Flasse, S., Pinty, B., & Tarantola, S. (2002). Designing a spectral index to estimate vegetation water content from remote sensing data: Part 1. Theoretical approach. *Remote Sens. Environ.*, *82*, 188–197.

Chandler, C., Cheney, P., Thomas, P., Trabaud, L., & Williams, D. (1983). *Forest Fire Behaviour Effects. Fire in Forestry, vol I*. New York: Wiley.

Chuvieco, E., Deshayes, M., Stach, N., Cocero, D., & Riaño, D. (1999). Short-term fire risk: foliage moisture content estimation from satellite data. In E. Chuvieco (Ed.), *Remote Sensing of large wildfires in the European Mediterranean Basin* (p. 228). Berlin: Springer.

Danson, F. M., Steven, M. D., Malthus, T. J., & Clarck, J. A. (1992). High-spectral resolution data for determining leaf water content. *Int. J. Remote Sens.*, *13*, 461–470.

Dawson, T. P., Curran, P. J., & Plummer, S. E. (1998). LIBERTY—modeling the effects of leaf biochemical concentration on reflectance spectra. *Remote Sens. Environ.*, *65*, 50–60.

Demarez, V., & Gastellu-Etchegorry, J. P. (2000). A modeling approach for studying forest chlorophyll content. *Remote Sens. Environ.*, *71*, 226–238.

Filella, I., & Peñuelas, J. (1994). The red edge position and shape as indicators of plant chlorophyll content, biomass and hydric status. *Int. J. Remote Sens.*, *15-7*, 1459–1470.

Fourty, T., & Baret, F. (1997). Vegetation water and dry matter contents estimated from top-of-the-atmosphere reflectance data: a simulation study. *Remote Sens. Environ.*, *61*, 34–45.

Ganapol, B. D., Johnson, L. F., Hammer, P. D., Hlavka, C. A., & Peterson, D. L. (1998). LEAFMOD: a new within-leaf radiative transfer model. *Remote Sens. Environ.*, *63*, 182–193.

Gao, B. -C. (1996). NDWI—a normalized difference water index for remote sensing of vegetation liquid water from space. *Remote Sens. Environ.*, *58*, 257–266.

Gao, B. -C., & Goetz, A. F. H. (1995). Retrieval of equivalent water thickness and information related to biochemical components of vegetation canopies from AVIRIS data. *Remote Sens. Environ.*, *52*, 155–162.

Gausman, H. W., Allen, W. A., Cardenas, R., & Richarson, A. J. (1970). Relation of light reflectance to histological and physical evaluations of cotton leaf maturity. *Appl. Opt.*, *9*, 545–552.

Goetz, A. F. H., Gao, B. -C., & Wessman, C. (1992). Vegetation biochemistry: what can imaging spectrometry tell us about canopies? *Proceedings of the 6th Australasian Remote Sensing Conference, Wellington, New Zealand, 2–6 November, Vol. 3*. (pp. 150–160).

Haboudane, D., Miller, J. R., Tremblay, N., Zarco-Tejada, P. J., & Dextraze, L. (2002). Integrating hyperspectral vegetation indices for accurate predictions of crop chlorophyll content for application to precision agriculture. *Remote Sens. Environ.*, *81*, 416–426.

Hunt, E. R., Rock, B. N., & Nobel, P. S. (1987). Measurement of leaf relative water content by infrared reflectance. *Remote Sens. Environ.*, *22*, 429–435.

Jacquemoud, S. (1993). Inversion of the PROSPECT + SAIL canopy reflectance model from AVIRIS equivalent spectra: theoretical study. *Remote Sens. Environ.*, *44*, 281–292.

Jacquemoud, S., Bacour, C., Poilve, H., & Frangi, J. P. (2000). Comparison of four radiative transfer models to simulate plant canopies reflectance—direct and inverse mode. *Remote Sens. Environ.*, *74*, 471–481.

Jacquemoud, S., & Baret, F. (1990). Prospect: a model of leaf optical properties spectra. *Remote Sens. Environ.*, *34*, 75–91.

Jacquemoud, S., Baret, F., Andrieu, B., Danson, F. M., & Jaggard, K. (1995). Extraction of vegetation biophysical parameters by inversion of the PROSPECT + SAIL models on sugar beet canopy reflectance data. Application to TM and AVIRIS sensors. *Remote Sens. Environ.*, *52*, 163–172.

Jacquemoud, S., Ustin, S. L., Verdebout, J., Schmuck, G., Andreoli, G., & Hosgood, B. (1996). Estimating leaf biochemistry using the PROSPECT leaf optical properties model. *Remote Sens. Environ.*, *56*, 194–202.

Kubelka, P., & Munk, F. (1931). Ein Beitrag zur Optik der Farbanstriche. *Ann. Techn. Phys.*, *11*, 593–610.

Kuusk, A. (1985). The hot spot effect of a uniform vegetative cover. *Sov. J. Remote Sens.*, *3*, 645–658.

Kuusk, A. (1998). Monitoring of vegetation parameters on large areas by the inversion of a canopy reflectance model. *Int. J. Remote Sens.*, *19*, 2893–2905.

Luther, J. E., & Carroll, A. L. (1999). Development of an index of Balsam Fir vigor by foliar spectral reflectance. *Remote Sens. Environ.*, *69,* 241–252.

Morais, M. (2001). Comparing spatially explicit models of fire spread through chaparral fuels: a new model based upon the Rothermel fire spread equation. MA thesis, University of California, Santa Barbara.

Parkinson, C. L., & Greenstone, R. (2000). EOS Data Products Handbook, Volume 2. EOS Project Science Office Code 900, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

Peñuelas, J., Filella, I., Biel, C., Serrano, L., & Savé, R. (1993). The reflectance at the 950–970 nm region as an indicator of plant water status. *Int. J. Remote Sens.*, *14*, 1887–1905.

Peñuelas, J., Gamon, J. A., Fredeen, A. L., Merino, J., & Field, C. B. (1994). Reflectance indices associated with physiological changes in nitrogen- and water-limited sunflower leaves. *Remote Sens. Environ.*, *48*, 135–146.

Peñuelas, J., Piñol, J., Ogaya, R., & Filella, I. (1997). Estimation of plant water concentration by the reflectance water index (R900/R970). *Int. J. Remote Sens.*, *18*, 2869–2875.

Pinzón, J. E., Ustin, S. L., Castañeda, C. M., & Smith, M. O. (1998). Investigation of leaf biochemistry by hierarchical foreground/background analysis. *IEEE Trans. Geosci. Remote Sens.*, *36*, 1–15.

Pyne, S. J., Andrews, P. L., & Laven, R. D. (1996). Introduction to Wildland Fire. (2nd ed.). New York: Wiley.

Roberts, D. A., Green, R. O., & Adams, J. B. (1997). Temporal and spatial patterns in vegetation and atmospheric properties from AVIRIS. *Remote Sens. Environ.*, *62*, 223–240.

Serrano, L., Ustin, S. L., Roberts, D. A., Gamon, J. A., & Peñuelas, J. (2000). Deriving water content of chaparral vegetation from AVIRIS data. *Remote Sens. Environ.*, *74*, 570–581.

Strahler, A. H., & Muller, J. P. (1999). MODIS BRDF/Albedo Product: Algorithm Theoretical Basis Document Version 5.0.

Ustin, S. L., Roberts, D. A., Pinzon, J., Jacquemoud, S., Gardner, M., Scheer, G., Castañeda, C. M., & Palacios-Orueta, A. (1998). Estimating canopy water content of chaparral shrubs using optical methods. *Remote Sens. Environ.*, *65*, 280–291.

Verhoef, W. (1984). Light scattering by leaf layers with application to canopy reflectance modelling: the SAIL model. *Remote Sens. Environ.*, *16*, 125–141.

Verstraete, M. M., Pinty, B., & Myneni, R. (1994). Understanding the biosphere from space: strategies to exploit remote sensing data. *Proc. 6th Int. Symp. Physical Measurements and Signatures in Remote Sensing, Val d'Isère, France, 17–21 January* (pp. 993–1004). Paris: CNES.

Willstatter, R., & Stoll, A. (1913). Untershuchunger uber die Assimilation der Kolhensaure. Berlin: Springer.

Woolley, J. T. (1971). Reflectance and transmittance of light leaves. *Plant Physiol.*, *47*, 656–662.

Zarco-Tejada, P. J., Miller, J. R., Mohammed, G. H., Noland, T. L., & Sampson, P. H. (1999). Optical indices as bioindicators of forest condition from hyperspectral CASI data. *Proceedings 19th Symposium of the European Association of Remote Sensing Laboratories (EARSeL), Valladolid, Spain*.

Zarco-Tejada, P. J., Miller, J. R., Noland, T. L., Mohammed, G. H., & 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 Trans. Geosci. Remote Sens.*, *39*(7), 1491–1507.

Zarco-Tejada, P. J., & Ustin, S. L. (2001). Modeling canopy water content for carbon estimates from MODIS data at land EOS validation sites. *International Geoscience and Remote Sensing Symposium, 2001. IGARSS '01, Vol. 1* (pp. 342–344).