Estimation of Vegetation Water Content with MODIS data and Radiative Transfer Simulation

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ABSTRACT- *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 NDWI and SRWI. 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, 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 field sampling campaign was undertaken for analysis of leaf water content from leaf samples in 10 study sites of chaparral vegetation in California, USA, between March and June 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 and viewing geometry values obtained from MOD09A1 product, and LAI from MOD15A2 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 content (r^2=0.7), showing that radiative transfer methods can be used for global monitoring of vegetation water content with MODIS.*

1 INTRODUCTION

Quantitative estimation of leaf biochemical and canopy biophysical variables is a key element in vegetation monitoring, a major goal in terrestrial ecology, and a long-term research objective given the complexity of the vegetation canopies and phenomena (Verstraete *et al.*, 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 (Peñuelas *et al.*, 1994), the study of the species and seasonal dependence (e.g. Belanger *et al.*, 1995), and may serve as bioindicators of vegetation stress (e.g. Luther and Carroll, 1999; Zarco-Tejada *et al.*, 2001). The remote determination of one of these biochemical constituents, vegetation water content, has important implications in forestry (Gao and Goetz, 1995), it is essential for drought assessment in natural vegetation, and it is a major driver in predicting the susceptibility to fire (Chandler *et al.*, 1983; Pyne *et al.*, 1996; Ustin *et al.*, 1998).

Several studies demonstrate the existing link between leaf-level reflectance in the 400-2500 nm spectral region and water in the leaf through optical indices and radiative transfer modeling (Gausman *et al.*, 1970; Jacquemoud and Baret, 1990; Ceccato *et al.*, 2001). 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, with indirect or secondary effects found at 400 nm, in the red edge at 700 nm. The broad use of leaf radiative transfer models such as PROSPECT (Jacquemoud and Baret, 1990) enable the simulation of the leaf optical properties as a function of structural and biochemical constituents such as chlorophyll a+b (Ca+b), dry matter (Cm), and leaf equivalent water thickness (Cw).

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. The

Normalized Difference Water Index (NDWI) calculated as (R860-R1240)/(R860+R1240) was suggested by Gao (1996) in a theoretical study, demonstrating its potential applicability for canopy-level water content estimation due to 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, R858/R1240) 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. The work presented here investigates the applicability of radiative transfer techniques to MODIS reflectance data for vegetation water content estimation. A simulation study with synthetic spectra and MODIS-equivalent spectra 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 leaf fuel moisture 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 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 Normalized Difference Water Index (NDWI, [(R860-R1240)/(R860+R1240)] (Gao, 1996), and the Simple Ratio Water Index (SRWI, R860/R1240) (Zarco-Tejada and Ustin, 2001) for vegetation water content estimation. The location of MODIS bands R1240 on the edge of the liquid water absorption (Figure 1), and R858 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 R858 and R1240 MODIS bands were demonstrated by Gao (1996) to cause small perturbations on these reflectance bands for remote estimation of water content.

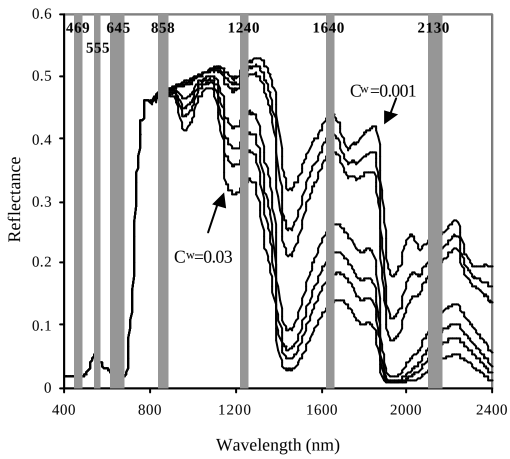

Figure 1. Modeling canopy-level reflectance using PROSPECT-SAILH models for different values of leaf water thickness (Cw=0.001 to Cw=0.03 cm) showing location of MODIS bands. PROSPECT parameters used were N=1.5, Cm=0.019 g/cm^2, and for SAILH LAI=5, plagiophile LADF, ts=35°, tv=0°, ps=0°.

The SRWI water index was studied through radiative transfer simulation to account for effects due to water content Cw, leaf dry matter Cm, and leaf internal structure N using the PROSPECT leaf model, for a range of values of Cw (in cm) and Cm (in g/cm^2) between 0.001 and 0.03, and N between 0.5 and 2.5. The primary variables affecting SRWI at the leaf level are Cw and N, with little effect of the Cm 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 Cm leaf variables need to be taken into account for accurate estimates of Cw 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 (ts), view angle (tv), and relative azimuth angle (ps). The simulation study illustrates the large effect of LAI on SRWI index calculated from canopy-level simulated reflectance and variable Cw (Figure 2). The simulation shows that SRWI is highly sensitive to the canopy structural parameter LAI, obtaining a 40% variation when SRWI is modeled with Cw=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.

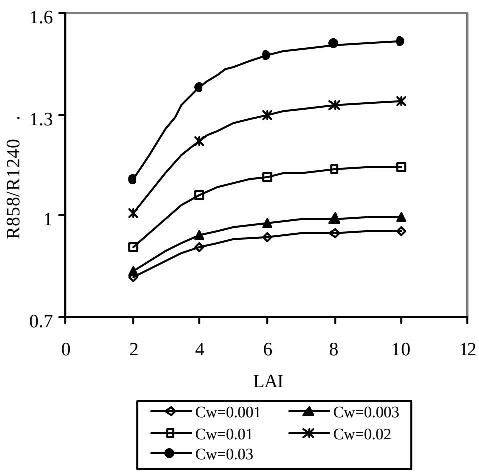

Figure 2. Modeling the effects of SRWI optical index at the canopy level as a function of LAI, and a range of equivalent water thickness values ranging from Cw=0.001 cm to Cw=0.03 cm. PROSPECT-SAILH were used for the simulation of leaf and canopy reflectance with other input parameters Cm=0.019 g/cm^2, N=1.5, Ca+b=50 µg/cm^2, plagiophile LADF, and viewing geometry ts=30º, tv=0º, and ps=0º.

The effects of soil reflectance on the SRWI index and on the absolute reflectance were studied with 3 soil spectra of extreme reflectance values in the 400-2500 nm range used as input in the PROSPECT – SAILH linked model. Simulation results obtained for low Cw values (Cw=0.001) to high equivalent water thickness (Cw=0.03) and for a LAI range of 1 to 10 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 Cw range, with no effects on the absolute reflectance. These results suggest that the effects of soil on canopy reflectance need to be considered when estimating Cw with low LAI, but showing that the primary drivers of SRWI variation are LAI and Cw, with less than 10% variation in SRWI for extreme soil values with low LAI.

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

3 ESTIMATION OF Cw BY MODEL INVERSION FROM MODIS-EQUIVALENT SYNTHETIC SPECTRA

A simulation study was conducted to study the spectral capability of MODIS for retrieving Cw 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), Ca+b (20-80 µg/cm^2), Cw (0.001-0.03 cm) and Cm (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 ts (10°-60°), tv (10°-60°), and ps (0°-180°). The leaf angle distribution function was set to plagiophile, and soil reflectance set to a nominal field-measured spectrum. 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).

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 Cw assessed under different assumptions. In this method of inverting a canopy reflectance model coupled with a leaf model (Jacquemoud, 1993; Jacquemoud *et al.* 2000; Kuusk, 1998; Demarez and Gastellu-Etchegorry, 2000; 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.

Results at the leaf level, therefore using only the PROSPECT model and four variables subject to inversion (N, Ca+b, Cw, and Cm) show that Cw can be estimated using the full spectrum (as previously demonstrated by Jacquemoud *et al.*, 1996) and using 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 Cw when four leaf variables N, Ca+b, Cw, and Cm are unknown. When pigment content is set to a fixed value (Ca+b=33 µg/cm^2 in this case), therefore guessing only N, Cw, and Cm, the determination coefficient obtained is r^2=0.93 when estimating Cw 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 R858 and R1240 nm reflectance bands in the function built for error calculation, results also demonstrate that Cw can be properly estimated when all four leaf variables are subject to inversion (r^2=0.97).

At the canopy level study with synthetic spectra, the four leaf variables N, Ca+b, Cw, and Cm were subject to inversion along with additional variables such as LAI, and viewing geometry ts, tv, and ps. When Cw 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 spectra are capable of estimating Cw when the three leaf parameters N, Cw, and Cm are subject to inversion, Ca+b is set to a fixed value, and LAI and viewing geometry are known (r^2=0.84 for full spectrum, and r^2=0.8 for MODIS-equivalent spectra). When the 4 leaf variables N, Ca+b, Cw, and Cm and the canopy LAI are inverted, determination coefficients for the full spectra is r^2=0.87, and r^2=0.67 for MODIS-equivalent spectra, demonstrating that inverting five variables at the same time with seven MODIS bands obtains worse results than when using the full spectrum. When Ca+b is set to a fixed value and N, Cw, Cm, and LAI are estimated, results are r^2=0.69 from the full spectrum, and r^2=0.53 from the MODIS equivalent spectra. These results demonstrate that MODIS equivalent spectra can be used to estimate Cw from canopy-level reflectance, obtaining r^2=0.99 if all other variables are known (N, Ca+b, Cm, LAI), r^2=0.8 if N, Cm, and Cw are inverted, Ca+b is fixed and LAI is known, r^2=0.67 if N, Ca+b, Cw, Cm, and LAI are estimated, and r^2=0.53 if N, Cw, Cm and LAI are estimated, with Ca+b fixed. The use of SRWI and NDWI indices as only components of the merit function fails at canopy level if more that 3 variables are subject to inversion, but obtaining r^2=0.69 if N, Cw, and Cm are estimated, Ca+b is fixed, and LAI is known. Results of this simulation study with synthetic MODIS-equivalent spectra demonstrate the theoretical capability of MODIS to estimate Cw by model inversion.

4 APPLICATION OF MODEL INVERSION METHODS TO MODIS DATA FOR WATER CONTENT ESTIMATION

A field sampling campaign was conducted for analysis of leaf fuel moisture content, measuring fresh and dry weight from leaf samples collected in 10 study sites of chaparral vegetation in California (USA) between March and June, 2000. Data collection was conducted as part of research work to study spatially explicit models of fire spread through chaparral fuels (Morais, 2001). MODIS reflectance data were obtained from the same period of field data acquisition for Cw estimation by model inversion linking the PROSPECT leaf model with the SAILH canopy reflectance model. Chaparral species sampled were *Adenostoma fasciculatum, Adenostoma sparsifolium, Artemisia californica, Ceanothus megacarpus, Salvia leucophylla,* and *Salvia mellifera* located within the area -118.913º long, 34.1523º lat and -118.5619º long, 34.0496º lat in California, USA (Figure 3).

MODIS surface reflectance product MOD09A1 (500m spatial resolution) and leaf area index (LAI) product MOD15A2 (1 km spatial resolution) were used for Cw 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). LAI (from MOD15A2 product), and reflectance, viewing geometry parameters sun angle (ts), view angle (tv) and relative azimuth angle (ps) (from MOD09A1 product) were extracted for every pixel in the composited reflectance image. The range of variation for the viewing geometry of all MODIS reflectance spectra used in this study was 11° to 38° for ts, 10° to 61° for tv, and -24° to 138° for ps.

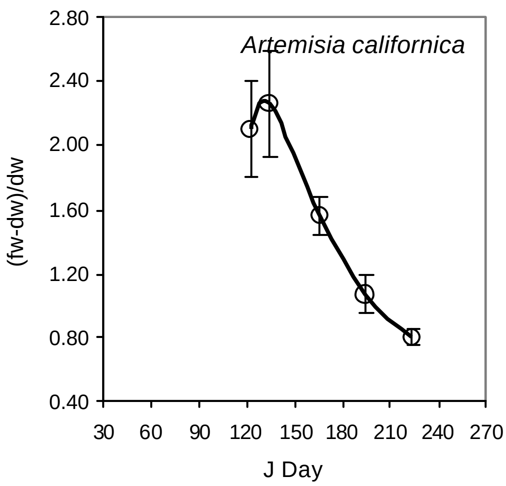

Figure 3. Leaf Fuel Moisture content (LFM) calculated as (fw-dw)/dw at one site for March-September 2000, showing the variation of leaf water content over time.

The time series of MODIS reflectance were used for inversion in the linked leaf - canopy reflectance model as described in the previous sections. The iterative optimization technique consisted of building the merit function with the SRWI optical index, as well as using all MODIS reflectance bands, with viewing geometry (ts, tv, and ps) and LAI from the MODIS products. Variables subject to inversion were the leaf structural parameter N, leaf dry matter Cm, and leaf equivalent water thickness Cw, with variables set to constant values in the inversion procedure Ca+b=33 μg/cm^2, plagiophile LADF, and soil spectral reflectance measured in the field. Estimation of leaf Cw by iterative optimization was compared with ground measured water content from each study site using the MODIS data coinciding with dates used for leaf sampling. Results obtained comparing the estimated Cw by inversion with the field-measured leaf fuel moisture content (Figure 4) demonstrated the capability of MODIS reflectance data to track changes of water content in vegetation. Cw estimated using SRWI index as merit function achieved r^2=0.54, obtaining better results r^2=0.7 when all MODIS bands are used in the model inversion, consistent with the simulation study performed in previous sections. These results suggest that seasonal estimates of leaf water content can be conducted by radiative transfer modeling from MODIS reflectance bands using inversion techniques.

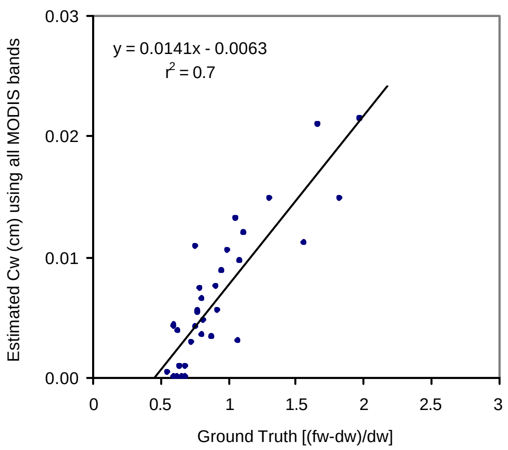

Figure 4. Relationship achieved between ground truth LFM [(fw-dw)/dw] measured in all study sites and Cw estimated by model inversion from MODIS reflectance using all reflectance bands for the period June-September 2000.

5 CONCLUSIONS

Simulation methods and results from the modeling and field studies described demonstrate that leaf water content can be globally monitored with MODIS data. 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. 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 estimation of Cw. Synthetic spectra were generated in two simulation studies at leaf and canopy levels using continuous reflectance and MODIS-equivalent spectra to study the capability of MODIS bands to successfully retrieve Cw by inversion. Inversion methods both at the leaf and canopy levels demonstrated that Cw could be successfully estimated by the MODIS bands when leaf variables N, Cw, and Cm are subject to inversion.

Model inversion methods proposed here for Cw estimation were confirmed using MODIS reflectance and ground data of leaf fuel moisture content collected between March and September 2000 from 10 study sites of chaparral vegetation in California (USA). MODIS reflectance, viewing geometry ts, tv, ps, and LAI were used as inputs for the model inversion. Successful results were found when comparing MODIS-estimated Cw with ground truth leaf fuel moisture (fw-dw)/dw from the study sites, obtaining r^2=0.7 when all MODIS bands are used for model inversion. This simulation and field study results suggest that a linked leaf-canopy radiative transfer approach can be used for global monitoring leaf water content from MODIS data and inversion methods.

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