UTILITY OF AN IMAGE-BASED CANOPY REFLECTANCE MODELING TOOL FOR REMOTE ESTIMATION OF LAI AND LEAF CHLOROPHYLL CONTENT IN CROP SYSTEMS

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ABSTRACT

Remotely sensed data in the reflective optical domain function as a unique cost-effective source for providing spatially and temporally distributed information on key biophysical and biochemical parameters of land surface vegetation. The challenging task of estimating leaf chlorophyll content (C_{ab}) and leaf area index (LAI) is here undertaken for crop systems in Maryland using a REGularized canopy reflectance (REGFLEC) modeling tool, which couples leaf optics (PROSPECT), canopy reflectance (ACRM), and atmospheric radiative transfer (6SV1) models. Using 10-m resolution SPOT-5 imagery, REGFLEC effectuated robust retrievals of C_{ab} and LAI for a diversity of agricultural fields characterized by a wide range in leaf chlorophyll and LAI levels with relative root-mean-square deviations on the order of 11 % and 15 %, respectively. REGFLEC is made entirely image-based by incorporating radiometric information from pixels belonging to the same land cover class during a LUT-based model inversion approach.

1. INTRODUCTION

Leaf area index (LAI) is a critical structural variable for understanding biophysical processes of vegetation canopies and for quantifying exchange processes of energy and matter between the land surface and the lower atmosphere [1]. Total leaf chlorophyll content (C_{ab}) can assist in determining photosynthetic capacity and productivity [2,3]. C_{ab} is also a good indicator of vegetation stress [4], is strongly related to leaf nitrogen content [5] and could therefore prove valuable for precision crop management [6].

Remote sensing techniques for estimating vegetation characteristics from reflective optical measurements have either been based on the empirical-statistical approach that links vegetation indices (VI) and vegetation parameters using experimental data, or on the inversion of a physical canopy reflectance (CR) model. While the empirical approach is simple and computationally efficient, there is no unique relationship between a sought vegetation parameter and a VI of choice, but rather a family of relationships, each a function of canopy characteristics, soil background effects and external conditions [7,8]. Physically-based models have proven to be a promising alternative as they describe the transfer and interaction of radiation inside the canopy based on physical laws and thus provide an explicit connection between the biophysical variables and the canopy reflectance.

The inversion process is ill-posed by nature due to measurement and model uncertainties and because different combinations of model parameters may correspond to almost identical spectra [9]. As a result, additional information is needed to accurately estimate the vegetation parameters. While the use of a priori knowledge (e.g. canopy type and architecture, model parameter ranges) has been shown to be an efficient way to solve ill-posed inverse problems [9,10], this regularization technique typically relies on the existence of experimental data collected at the site of interest. [7] demonstrated how the temporal evolution of LAI could be utilized as another way of regularizing the inverse problem and [11, 12, 13] demonstrated how to take advantage of the spectral radiometric information of pixels belonging to the same land cover type.

In this paper the C_{ab} and LAI retrieval capabilities of the REGularized canopy reflectance (REGFLEC) modeling tool [13] are demonstrated for crop systems in Maryland.

2. METHODS

A schematic diagram of the REGularized canopy reflectance (REGLEC) modeling tool [13], linking atmospheric radiative transfer (6SV1) and inverse canopy reflectance modeling (ACRM-PROSPECT), is given in Fig. 1. Given inputs of remotely sensed at-sensor radiance observations in the green (ρ_{green}), red (ρ_{red}) and near-infrared (ρ_{nir}) wavebands, a few atmospheric state parameters, and pre-generated soil and land cover classifications, the model computes key biophysical properties (C_{ab} and LAI) by considering fairly wide variations in leaf structure (N), vegetation clumping (S_z), leaf inclination angle (θ_l), fraction of senescent vegetation (f_B) and soil reflectance (s_1).

The vector version of 6S (Second Simulation of the Satellite Signal in the Solar Spectrum) atmospheric radiative transfer model (6SV1) [14,15] is in REGFLEC used to convert at-sensor radiance to directional surface reflectance. 6SV1 input parameters include sun zenith (θ_s), satellite view zenith (θ_v) and relative azimuth (θ_{raz}) angles, total column ozone content (O_3), total precipitable water (TPW), aerosol optical depth at 550 nm (τ_{550}), and type of aerosol model (τ_{type}) (Fig. 1).

The biophysical parameter retrievals are facilitated using a LUT-based inversion approach. The turbid medium Markov chain canopy reflectance model, ACRM [16] coupled to the leaf optics model PROSPECT [17] is run in forward mode with site-specific view-sun angles to generate LUTs with a suite of simulated LAI – ρ_{nir}, LAI – NDVI, LAI – GNDVI, and C_{ab} – ρ_{green} relationships across the model parameter distribution space [13], where GNDVI is the NDVI using the green rather than the red spectral band. These spectral relationships vary considerably as a function of canopy characteristics and soil background effects [12,13], which much be effectively corrected for in order to estimte C_{ab} and LAI accurately using the stored LUT-based relationships.
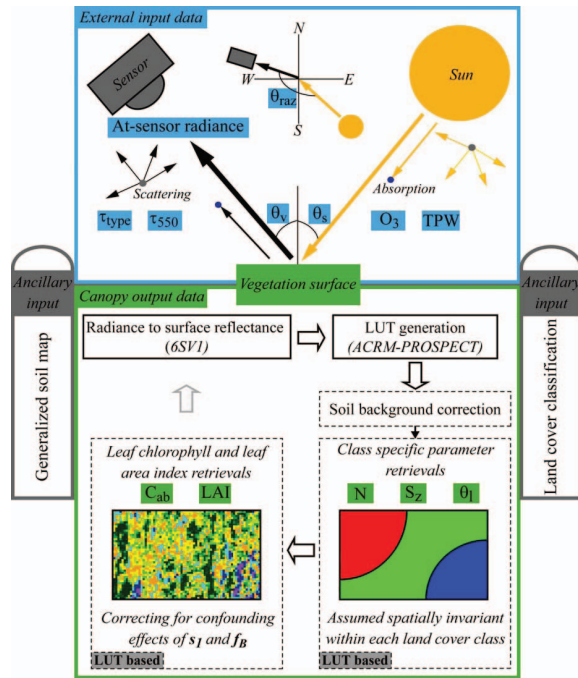
Fig. 1 A schematic diagram of the coupled 6SV1 – ACRM – PROSPECT biophysical parameter retrieval tool (REGFLEC). Parameter descriptions are given in the text.

Ancillary information on the spatial distribution of soil types is used to aid the determination of background effects. At low vegetation coverage, a mismatch in LAI estimated using observations of ρ_{nir} (LAI – ρ_{nir}), NDVI (LAI – NDVI) and GNDVI (LAI – GNDVI), respectively is most likely due to erroneous soil reflectance (s_1) values, as the relationships are minorly influenced by canopy characteristics (when the vegetation amount is low) but differ distinctly in their response to variations in soil reflectance [13]. As the LAI estimates generated as a function of observed ρ_{nir}, NDVI and GNDVI, respectively should coincide if the background effect is properly accounted for, s_1 is adjusted to cause matching LAI values for each low vegetation density pixel. The LUT-based retrievals of s_1 are then averaged for each soil type and extrapolated to pixels with intermediate to high vegetation coverage using the soil map.

In the next step (Fig. 1), leaf structure (N), vegetation clumping (S_z) and leaf inclination angle (θ_l) are estimated as described in [13] based on the assumption that they show little variability within each land cover class [11]. Only the spectral information content from high vegetation density pixels (NDVI > 0.65) is used for this purpose, thereby maximizing the sensitivity of the reflectance signal to the leaf and canopy variables while reducing the confounding influence of the background reflectance signal.

Finally, pixel-wise estimates of C_{ab} and LAI are generated by accessing (LUT) the appropriate soil and land cover specific spectral reflectance relationships and by iteratively adjusting the fraction of senescent vegetation (f_B) and to a lesser extent s_1 to provide a match betweem LAI values generated as a function of observed ρ_{nir}, NDVI and GNDVI, respectively.

3. FIELD EXPERIMENT

REGFLEC was applied to a non-irrigated agricultural area located in proximity to the USDA-ARS Beltsville Agricultural Research Center, Maryland (39.02º N, 76.85º W) (Fig. 2). The study focuses on data collected during two intensive weeklong campaigns at the end of July and August 2007.

3.1 Biophysical measurements

Measurements of LAI and leaf chlorophyll were collected between July 27th and August 3rd and August 27[tt] and August 31st at 40 plots within fields of soybean, grass, alfalfa and corn. Each plot was approximately circular with a radius of 10 m and geolocated using handheld global positioning systems units (accuracy ≈ 4 m). Non-destructive LAI measurements were made shortly after sunrise using a LAI-2000 instrument (LiCor, USA). For corn crops, readings were made along diagonal transects between the rows as suggested in the LAI-2000 manual for row crops.

Leaf chlorophyll was measured non-destructively with a portable SPAD-502 Chlorophyll meter (Spectrum Technologies, Inc.). Six separate measurments were made on each leaf to properly describe the variability across the leaf and for each plot the average of approximately 50 x 6 SPAD readings was used. The relationship used to convert the non-dimensional SPAD measurements into leaf chlorophyll content ($\mu g\ cm^{-2}$) is based on a spectrophotometrical analysis of leaf samples (maize) collected during the first field campaign and is given as

$$C_{ab} = 33.90 \cdot \exp(SPAD \cdot 0.0196) - 37.15 \quad (\text{rmsd} = 4.1\ \mu g\ cm^{-2}) \qquad (1)$$

3.2 Satellite and ancillary observations

Radiance data in the green (500-590 nm), red (610-680 nm) and near-infrared (780-790 nm) wavebands were acquired by the SPOT-5 High Resolution Geometric imaging instrument (HRG-1) on July 27th and August 27th. The SPOT-5 radiances were obtained in 10 m resolution at around noon local time for 30x30 km image swaths. The data were rectified using nearest-neighbor resampling to match a standard cartographic projection (UTM WGS84).

The level 1.5 Aerosol Robotic NETwork (AERONET) aerosol optical depth (τ_{550}) and total precipitable water (TPW) data from the nearby NASA GSFC site were used as input to 6SV1 in addition to atmospheric ozone measuremenst (O_3) from the Atmospheric InfraRed Sounder (AIRS) level 2 standard retrieval product.

A land cover classification of the region was generated based on visual inspection of the agricultural fields.

4. RESULTS AND CONCLUSIONS

Fig. 2 showcases REGFLEC LAI and C_{ab} retrieval results for a subset of the study area. Leaf chlorophyll content shows significant spatial heteorogeneity during both SPOT overpasses, varying from 15 – 85 $\mu g\ cm^{-2}$. High C_{ab} values tend to coincide with high amounts of leaf biomass. The low C_{ab} values observed within some fields with intermediate to high density vegetation amounts may suggest stressed field conditions. The July 27th overpass was at the end of a prolonged drought in the region and many fields experienced stressed conditions. At this time the corn fields were in a late stage of maturity with beginning leaf senescence in many
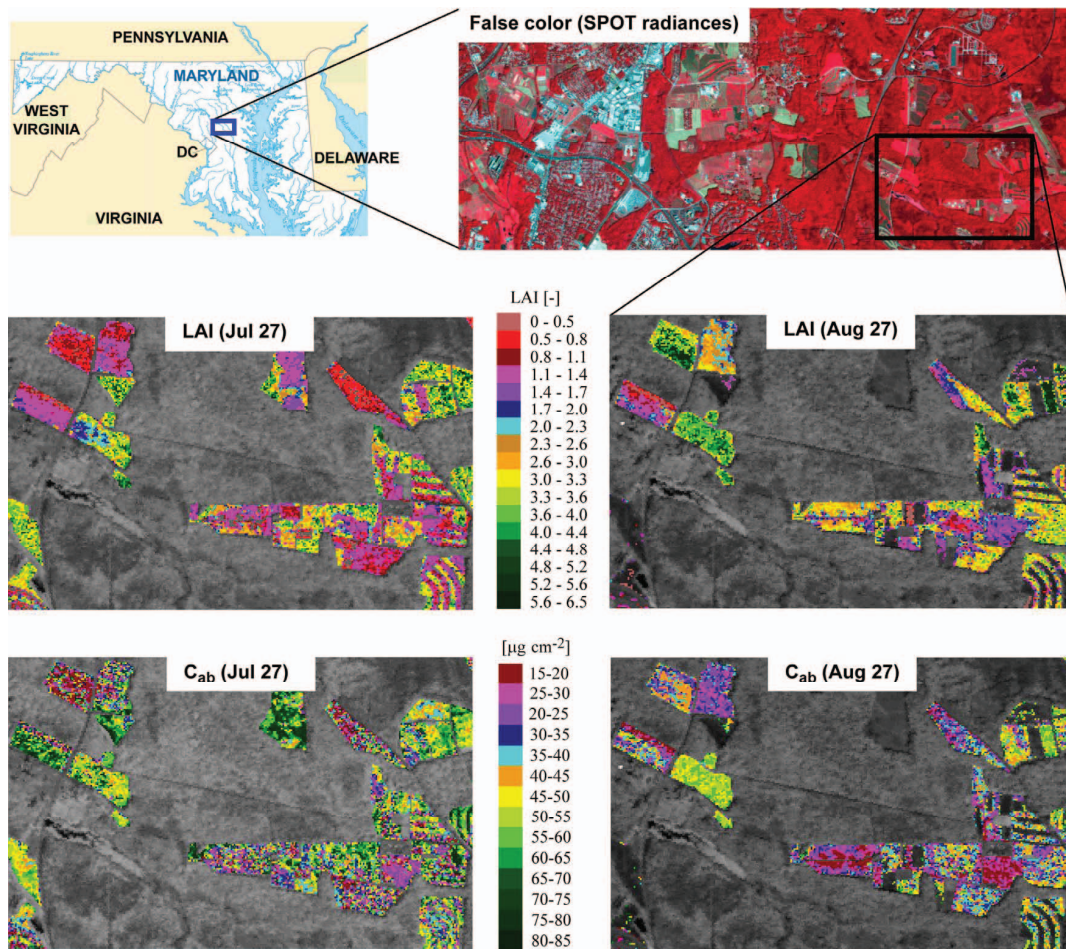
Fig. 2 Study site and sample showcases of LAI and leaf chlorophyll retrievals for crop systems during the two SPOT-5 satellite acquisitions. The grey-scale background is SPOT-5 near-infrared reflectances and primarily represents forested land.

places. The soybean fields were beginning to senescence at the August 27th overpass.

The extreme environmental and plant development conditions allowed for model validation over a wide range in LAI and leaf chlorophyll content for the complex case of green leaf material intermixed with senescent material. The model shows excellent capability in reproducing the pattern in LAI (Fig. 3a) and C_{ab} (Fig. 3b) measured in fields of soybean, grass, alfalfa and corn with relative root-mean-square deviations (rmsd) of 15% and 11%, respectively. High LAI prediction abilities are observed over the entire range of LAI values (0.5 – 6).

REGFLEC faciliated reliable biophysical parameter retrievals using image-based techniques and with moderate input requirements: 1) At-sensor radiance data in 3 spectral bands available on practically any airborne and satellite based sensor system. A key advantage is the direct use of readily available radiance data as REGFLEC couples atmospheric correction (6SV1) and canopy reflectance modeling routines, 2) Atmospheric state parameters that can all be acquired with reasonable accuracy from operational satellite products, 3) Land cover classification, and 4) Soil map.

The preliminary insight into REGFLEC LAI and C_{ab} mapping capabilities is encouraing. Work is currently in progress to evaluate the usefulness and possible limiations of the model for other environments and species compositions and for other airborne and satellite sensor systems.

5. REFERENCES

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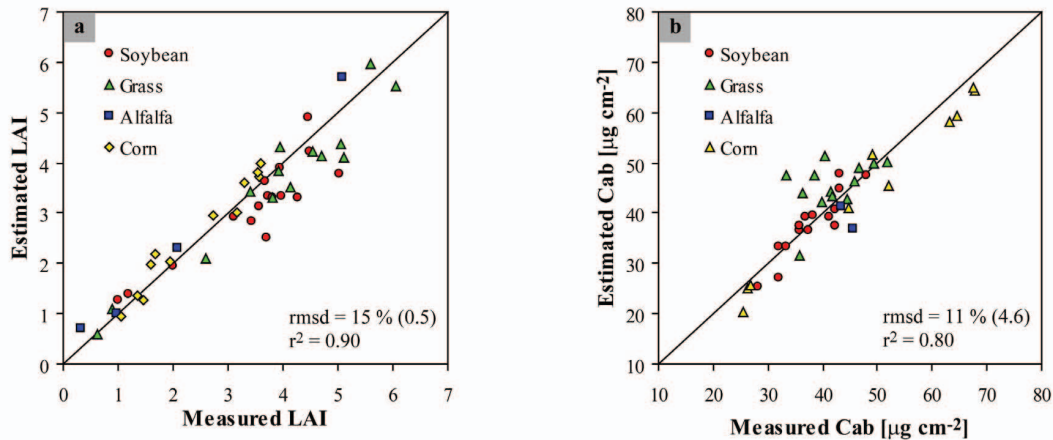
Fig. 3 Validation of 10 m resolution LAI (a) and leaf chlorophyll (b) estimates against field measurements collected within circular 10 m radius field plots. The r^2 value and the relative and absolute root-mean-square-deviation (rmsd) between estimates and measurements are listed. The line is the 1:1 line.

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