COMBINING OBSERVATIONS IN THE REFLECTIVE SOLAR AND THERMAL DOMAINS FOR IMPROVED CARBON AND ENERGY FLUX ESTIMATION

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ABSTRACT

This study investigates the utility of integrating remotely sensed estimates of leaf chlorophyll (C_{ab}) into a thermal-based Two-Source Energy Balance (TSEB) model that estimates land-surface CO2 and energy fluxes using an analytical, light-use-efficiency (LUE) based model of canopy resistance. The LUE model component computes canopy-scale carbon assimilation and transpiration fluxes and incorporates LUE modifications from a nominal (species-dependent) value (LUE_n) in response to variations in environmental conditions. However LUE_n needs adjustment on a daily timescale to accommodate changes in plant physiological condition and nutrient status. Day to day variations in LUE_n were assessed for a corn crop field in Maryland U.S.A. through model calibration with CO_2 flux tower observations. The optimized daily LUE_n values were then compared to estimates of C_{ab} integrated from gridded maps of chlorophyll content weighted over the tower flux source area. The time-continuous maps of daily C_{ab} over the study field were generated by fusing in-situ measurements with retrievals generated with an integrated radiative transfer modeling tool using at-sensor radiances in green, red and near-infrared wavelengths acquired with an aircraft imaging system. The resultant daily changes in C_{ab} within the tower flux source area exhibited a curvilinear relationship with corresponding changes in daily calibrated LUE_n values derived from the tower flux data, and hourly water, energy and carbon flux estimation accuracies from TSEB were significantly improved when using C_{ab} for delineating spatio-temporal variations in LUE_n. The applicability of the established relationship between LUE_n and C_{ab} is currently being tested for an agricultural area near Bushland, Texas using a combination of reflective and thermal satellite imagery from SPOT, Landsat and ASTER.

INTRODUCTION

In the absence of clouds, remotely sensed observations in the reflective solar and thermal infrared (TIR) domains have great utility for monitoring the terrestrial biosphere and vegetation dynamics at a range of spatial and temporal scales. The satellite signal in these wavebands is indirectly related to a variety of key biophysical and vegetation biochemical descriptors of the land surface that are needed for reliable assessments of land-surface carbon, water and energy fluxes. Accurate means for monitoring surface fluxes over regional scales have utility in water resource management, yield forecasting, and numerical weather prediction. Biophysical quantities derivable from reflective band imagery include leaf area index (LAI), which serves as a key determinant for variations in land surface fluxes of carbon, water and energy (Bonan, 1995), and leaf chlorophyll content (C_{ab}), which is an important indicator of the overall plant physiological condition. Since chlorophylls absorb photosynthetically active radiation they function as vital pigments for photosynthesis, and C_{ab} has been found useful for detecting vegetation stress (Zarco-Tejada et al., 2002) and leaf nitrogen deficiency (Daughtry et al., 2000), and for monitoring vegetation productivity (Gitelson et al., 2006). The benefits of using thermal infrared remote sensing for monitoring land surface fluxes are well documented (Kustas and Anderson, 2009). Thermal infrared data provide valuable information about the sub-surface moisture status, obviating the need for precipitation input and prognostic modeling of the soil water balance (Anderson et al., 2008). Radiometric surface temperatures can be an effective substitute for in-situ surface moisture observations (Zhan and Kustas, 2001), and have the ability to capture subtle signatures of soil moisture deficiencies and reduced stomatal aperture (Anderson et al., 2008).

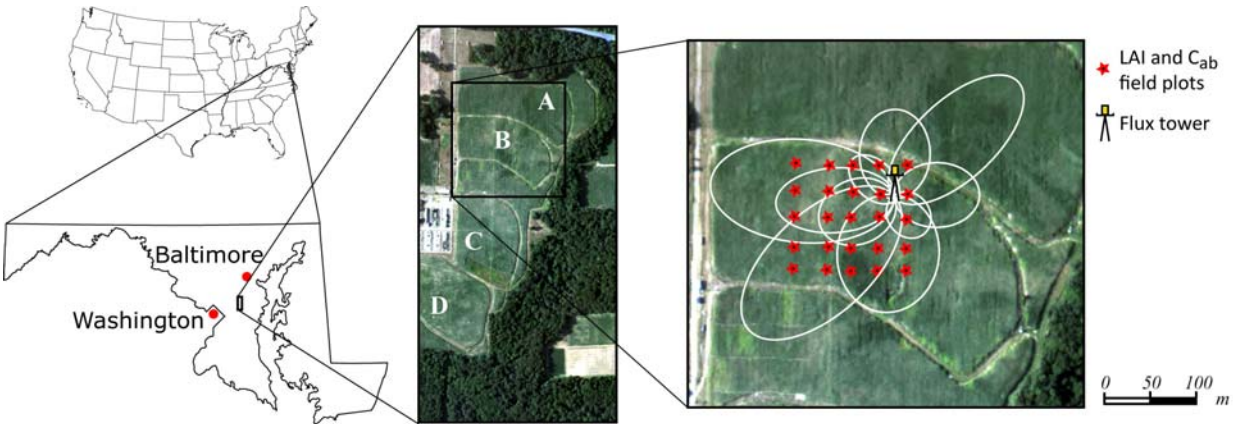

Figure 1. Natural color aircraft imagery mosaic (1 m resolution) of the OPE3 corn field (labeled B) in Maryland with a blowup of the area in immediate vicinity of the flux tower. Locations of LAI and leaf chlorophyll (Cab) sampling sites are indicated by the red stars. 90% source areas of the flux tower CO2 fluxes at the time of midday are depicted for a collection of days.

Chlorophyll content is being increasingly recognized as a key for quantifying photosynthetic efficiency and gross primary production of terrestrial vegetation (Gitelson et al., 2008; Zhang et al., 2009; Wu et al., 2009). Recently, Houborg et al. (2009a) and Houborg & Anderson (2009) developed the REGularized canopy reFLECtance (REGFLEC) tool that integrates leaf optics (PROSPECT), canopy reflectance (ACRM), and atmospheric radiative transfer (6SV1) model components, facilitating direct use of at-sensor radiance observations in green (~510-580 nm), red (~610-690 nm), and near-infrared (~800-900 nm) wavelengths for the retrieval of C_{ab} and LAI at a range of spatial scales. Relative root-mean-square deviations for both variables were typically on the order of 10 - 15 % for the studied cases. While reliable remote sensing based C_{ab} retrievals may be feasible, the question remains how to use this new information content to parameterize land surface models for improved flux predictability.

This study investigates how C_{ab} estimates can be used to parameterize photosynthetic efficiency within a modified form of the thermal-based Two-Source Energy Balance (TSEB) model (Norman et al., 1995), which implements an analytical, light-use-efficiency (LUE) based model of canopy resistance to estimate coupled carbon, water and heat fluxes from the land-surface (Anderson et al., 2008). The LUE model component computes canopy-scale carbon assimilation and transpiration fluxes and incorporates LUE modifications from a nominal (typically species-dependent) value (LUE_n) in response to variations in environmental conditions. A specific objective is to analyze the correlation of C_{ab} with LUE_n that may need further adjustment on a daily timescale to accommodate changes in plant phenology, physiological condition and nutrient status.

METHODS

Study site

Aircraft imagery, flux observations and in-situ measurements were collected over a corn (Zea mays L.) crop field located within the USDA-ARS Beltsville Agricultural Research Center, Maryland (39.02° N, 76.85° W) (Figure 1). The study site is associated with the Optimizing Production Inputs for Economic and Environmental Enhancement (OPE3) program, and consists of four surface hydrologically bounded subwatersheds, about 4 ha each, which feed a wooded riparian wetland and first-order stream. The watersheds were formed from sandy fluvial deposits and have a varying slope ranging from 1% to 4% (for further details see http://hydrolab.arsusda.gov/ope3/). This study focuses on data collected from day of year (doy) 153 to 220 during the 2007 growing season, spanning the period from approximately 3 weeks after leaf emergence, through corn tasseling and silking, and into a stage of leaf senescence. The average daily mean temperature for June and July was 22.3° and 24.2°, respectively, and the precipitation was well below average from around mid-June. This resulted in significant crop drought stress in the latter part of the study period.

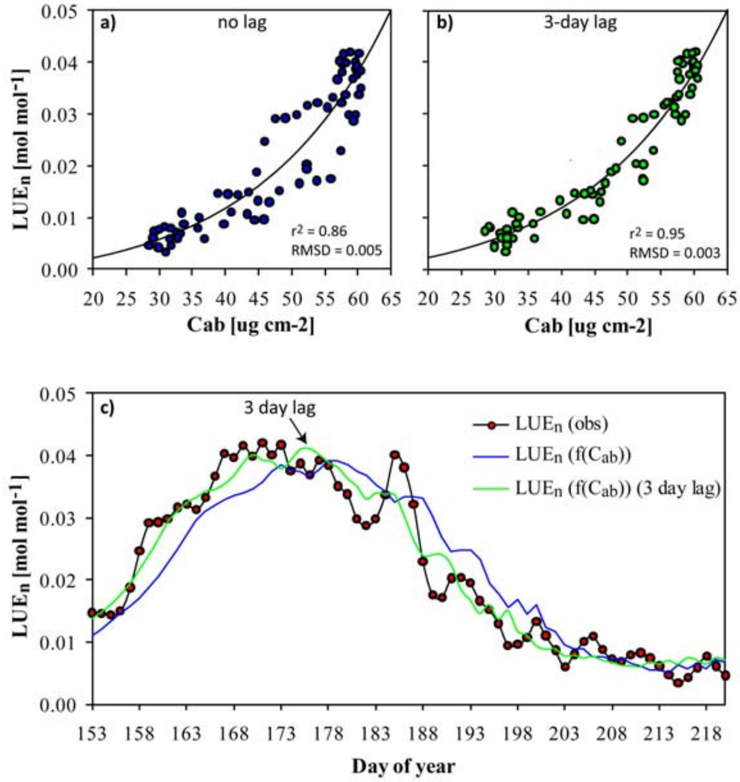

Figure 2. Scatter plots of model calibrated LUEn and footprint averaged leaf chlorophyll content and associated exponential fits with (a) and without (b) a 3-day lag is applied to the leaf chlorophyll timeseries record. c) Timeseries intercomparison plot of model calibrated LUEn and LUEn estimated as exponential functions of Cab. The improved agreement with the lagged Cab estimates suggest that short-term environmental stresses are not immediately manifested in the Cab record.

Image-based LAI and C_{ab} Retrievals

Spatial estimates of C_{ab} and LAI were derived from aerial imagery acquired on July 21st 2007 (DOY 201) using the REGularized canopy reFLECtance retrieval tool (REGFLEC) (Houborg et al., 2009a; Houborg and Anderson, 2009). Digital image data in the green (510-580 nm), red (610-690 nm) and near-infrared (800-900 nm) wavelength regions were provided at a spatial resolution of 1 m during conditions of significant degrees of plant stress resulting from a prolonged period of extreme environmental conditions. The REGFLEC integrated system of radiative transfer models (atmosphere - canopy - leaf) facilitates biophysical parameter retrievals directly from at-sensor radiance data in the three broad spectral bands. REGFLEC adopts a multi-step look-up table based inversion approach and incorporates various image-based techniques to reduce the confounding effects of land cover specific vegetation parameters and soil reflectance. Atmospheric state variables to describe atmospheric scattering and absorption characteristics, solar and sensor view angle geometries, and a land cover and soil map are additional input requirements of the model. A comprehensive description of the REGFLEC LAI and C_{ab} retrieval products for the corn field at OPE3 is provided in Houborg et al. (2009a), who validated the products to ~ 10% accuracy (relative root-mean-square deviation) using in-situ data collected at 2x2 m field plots (Figure 1) in addition to supplementary data collected at 6 larger plots (15 m x 15 m). Atmospheric state data of aerosol optical depth and total precipitable water used in REGFLEC, came from the nearby NASA GSFC AERONET site, whereas atmospheric ozone measurements were extracted from the Atmospheric InfraRed Sounder (AIRS) level 2 standard retrieval product (Houborg et al., 2009a).

Correlating C_{ab} with Light-use-efficiency

The image-based LAI and C_{ab} retrievals at the aircraft overpass time were fused with weekly in-situ measurements in order to generate a continuous spatial LAI and C_{ab} record spanning the period from doy 153 to 220.

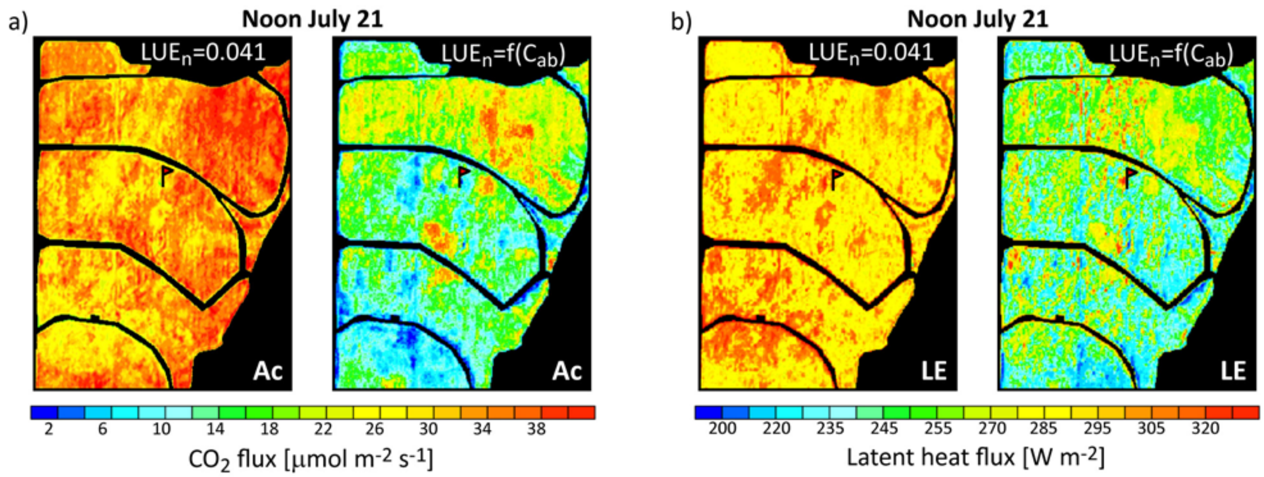

Figure 3. Maps of CO2 flux (a) and latent heat flux (b) at the time of the aircraft overpass comparing TSEB_LUE model runs using LUEn parameterized as a function of remotely sensed Cab (right panels) and runs assuming a fixed value for the entire field (left panels).

The fusion approach adopted here assumes that (1) the relative temporal evolution of LAI and C_{ab} at any point (pixel) within the field follows the temporal characteristic at one of the in-situ sampling sites (Figure 1), and (2) spatial pattern anomalies of LAI and C_{ab} present during the aircraft acquisition are preserved. Daily LAI and C_{ab} maps were generated from the weekly retrievals by linear interpolation.

A land surface model calibration approach was then adopted to generate a daily time-series of nominal light-use-efficiencies (LUE_n) for comparison with the daily C_{ab} maps. The prognostic canopy-scale model of atmosphere-land exchange (ALEX) (Anderson et al., 2000) was used for this purpose. A LUE-based model of canopy resistance is embedded in ALEX for computing coupled carbon and assimilation fluxes. While the LUE model component estimates modifications in LUE from the nominal (presumably species-dependent) value (LUE_n) in response to variations in light environment, atmospheric humidity, CO2 concentration, and soil moisture content, LUE_n may need further adjustment on a daily timescale to accommodate changes in plant phenology, physiological condition, and vegetation nutrient status. A calibration of ALEX against CO2 flux tower observations was carried out to test the variability in LUE_n over the study period (doy 153-220). The calibration assumes that discrepancies between model estimated (ALEX) and observed (eddy covariance) CO2 fluxes can be attributed entirely to variations in LUE_n. This approach is assumed viable given that LUE_n is the primary control on the CO2 flux for intermediate to densely vegetated canopies (Houborg et al., 2009b). Daily LUE_n inputs to ALEX were varied over a prescribed range and optimized by minimizing the root-mean-square (RMS) deviation between the modeled and observed canopy assimilation fluxes on a daily scale (constrained to the 9 am - 17 pm daytime period). The end product of this exercise is a time-series of daily calibrated LUE_n values characteristic of the average surface footprint sampled by the flux tower on any given day. These were then compared with daytime leaf chlorophyll estimates extracted from the daily C_{ab} maps.

RESULTS AND DISCUSSION

LUE_n - C_{ab} Inter-correlation

Figure 2c plots the daily evolution of model calibrated nominal LUE values, derived by minimizing the RMS error between CO2 model estimations from the prognostic ALEX model and tower flux observations, and corresponding LUE_n values estimated as a function of image-based estimates of C_{ab} within the footprint of the flux tower (Figure 2a and b). While the calibration procedure may be overly simplistic in assuming that the difference between estimated and observed CO2 flux is attributable entirely to LUE_n variability, the maximum LUE_n (0.041) is in agreement with literature values on LUE_n for irrigated or highly productive corn sites (Houborg et al., 2009b). The C_{ab} estimates are seen to be very useful for tracking the overall seasonal trend in LUE_n; specifically the rapid increase during leaf expansion and development (doy 153 - 165), peak values during the early stages of leaf maturity

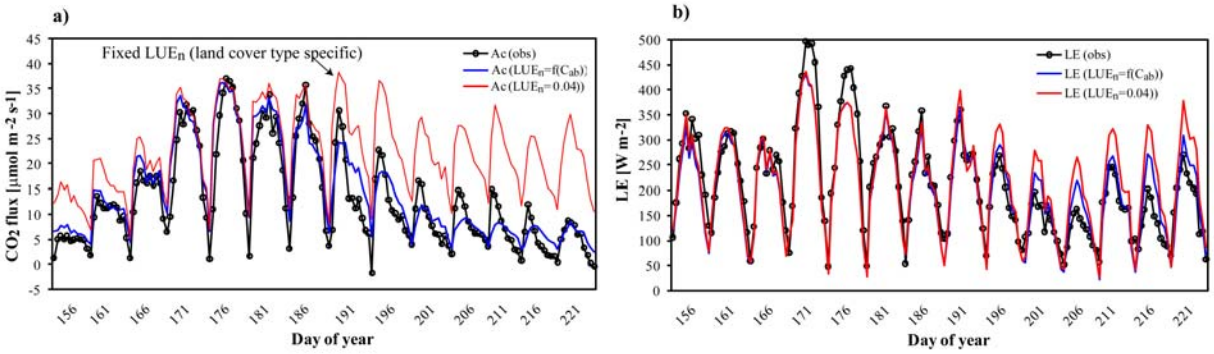

Figure 4. Comparison of hourly eddy covariance flux observations with model estimates of CO2 (a) and latent heat (b) generated with the TSEB_LUE using a fixed LUEn and a LUEn that varied seasonally as a function of leaf chlorophyll (Eq. 4). Each diurnal segment represents flux data averaged by hour over 5-day intervals.

and the fairly rapid decrease initiating around doy 185 and continuing through leaf senescence, which is similar to measurement results reported for photosynthetic capacity in temperate deciduous forests (Wilson et al., 2000). The relationship between LUE_n and C_{ab} is best described by an exponential function (Figure 2a and b) and the relationship is improved when a 3-day lag is applied to the C_{ab} record (e.g. C_{ab} data from doy 162 is shifted to doy 159) (Figure 2b). The exponential fit to the unlagged and lagged data yields R^2 values of 0.86 and 0.95 and RMS errors 0.005 mol mol^{-1} and 0.003 mol mol^{-1}, respectively. The importance of the 3-day C_{ab} lag is clearly evident in the timeseries intercomparison plot of model calibrated LUE_n and LUE_n estimated as exponential functions of C_{ab} (Figure 2c), which may suggest that environmental stresses are not immediately manifested in the C_{ab} record.

Utility of C_{ab} for Optimizing FLux Estimates

A thermal-based Two-Source Energy Balance (TSEB) land-surface model that implements a LUE-based transpiration/assimilation sub-model (TSEB_LUE) (Anderson et al., 2008) was adopted for evaluating the utility of the remote sensing based leaf chlorophyll dataset in association with thermal data for optimizing CO2, water and heat flux estimates

The use of spatially variable values of LUE_n, retrieved from remote sensing estimates of C_{ab} as prescribed by the exponential relationship (Figure 2), has a pronounced effect on simulated (TSEB_LUE) carbon and water fluxes within the corn field at the time of the aircraft overpass (Figure 3). The map of C_{ab} displayed significant spatial heterogeneity on this day as a result of prolonged drought conditions in interaction with subsurface flow pathways (Houborg et al., 2009a), which in effect increased the dynamic range and intra-field variability in CO2 (Figure 3a) and latent heat fluxes (Figure 3b) significantly. In contrast, flux maps generated using a fixed, spatially uniform value of LUE_n exhibit fairly homogenous conditions. Parameterizing LUE_n as a function of C_{ab} has the effect of reducing CO2 and latent heat fluxes in severely stressed parts of the field from ~26 to ~2 µmol m^{-2} s^{-1} and from ~300 to ~200 W m^{-2}, respectively (Figure 3).

Figure 4 demonstrates the ability of TSEB_LUE to reproduce temporal (diurnal and seasonal) patterns and magnitudes of carbon and water exchange within the footprint of the flux tower. For illustrative purposes, each diurnal segment represents flux data averaged by hour over 5-day intervals. This serves to reduce random errors in the flux observations and the natural variability that is associated with individual periods (Moncrieff et al., 1996). Consideration of temporal changes in LUE_n (as dictated by variations in C_{ab}) improves the accuracy of simulations of carbon uptake by the corn field, particularly during leaf expansion and development (doy 156 - 171) and late stages of leaf maturity and leaf senescence (> doy 191), where observed fluxes otherwise would be vastly overestimated (Figure 4a). The validity of using a fixed optimal LUE_n (0.041) appears to be limited to the early stages of leaf maturity beginning around doy 171 (Figure 4a). Severe environmental stresses on the vegetation in combination with advancing leaf senescence amplify the carbon flux overestimation during the latter part of the flux record, which may reach 400 % if TSEB_LUE does not account for temporal changes in LUE_n (Figure 4a). While C_{ab} is primarily linked to vegetation productivity (i.e. CO_2 exchange), it also has potential for improving estimates of latent heat flux from the LUE-based Two-Source Energy Balance model (Figure 4b).

CONCLUSION

The results from this study indicate significant potential for using remotely sensed leaf chlorophyll content for quantifying variability in photosynthetic efficiency across a heterogeneous corn field that was exposed to severe environmental stresses during the 2007 drought in Maryland, U.S.A. Maps of daily leaf chlorophyll, derived by fusing in-situ and image-based inferences, were well-correlated with temporal changes in nominal light-use-efficiency (LUE), which is used as a key input to a thermal-based two-source energy balance framework that implements a LUE-based model of stomatal conductance (TSEB_LUE) for coupling carbon and water fluxes.

Comparison with flux tower eddy covariance observations demonstrated improved utility of TSEB_LUE to reproduce temporal patterns and magnitudes of carbon, water and energy exchange when using leaf chlorophyll to prescribe temporal changes in nominal LUE. The use of a seasonally fixed nominal LUE may lead to significant flux overestimations during leaf development and leaf senescence and during environmentally stressed conditions.

The results from this study point toward a functional relationship between nominal LUE and leaf chlorophyll that may be applicable to other environments and species compositions. A similar analysis on the utility of satellite-based retrievals of LAI and leaf chlorophyll for optimizing CO2 and energy fluxes for a wider range of crops is currently in progress using satellite and ground-based data collected in 2008 over an agricultural area in and around the Conservation and Production Research Laboratory, USDA-ARS, Texas (35.19° N, 102.06° W) during the Bushland Evapotranspiration and Agricultural Remote Sensing EXperiment (BEAREX08).

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