INTEGRATING SATELLITE RETRIEVED LEAF CHLOROPHYLL INTO LAND SURFACE MODELS FOR CONSTRAINING SIMULATIONS OF WATER AND CARBON FLUXES

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ABSTRACT

In terrestrial biosphere models, key biochemical controls on carbon uptake by vegetation canopies are typically assigned fixed literature-based values for broad categories of vegetation types although in reality significant spatial and temporal variability exists. Satellite remote sensing can support modeling efforts by offering distributed information on important land surface characteristics, which would be very difficult to obtain otherwise. This study investigates the utility of satellite based retrievals of leaf chlorophyll for estimating leaf photosynthetic capacity and for constraining model simulations of water and carbon fluxes.

Index Terms— CLM, leaf chlorophyll, Landsat, GPP

1. INTRODUCTION

Reliable assessments of the exchanges of water and carbon between soil, vegetation and atmosphere remain critically important for improving our understanding of ecosystem functioning, for establishment of regional and global carbon budgets, for agricultural management and yield forecasting, and drought monitoring activities to name a few. State of the art terrestrial biosphere models (TBM) include comprehensive descriptions of biogeophysical and biogeochemical processes to facilitate realistic simulations of terrestrial ecosystem exchanges. While these models are characterized by improved process understanding and descriptions, the downside of the enhanced complexity is additional land-surface parameters that can be challenging to define with acceptable accuracy over spatial and temporal domains, significantly hampering the ability to describe spatial and interannual variability of terrestrial carbon and water fluxes [1]. TBMs typically simulate CO2 assimilation of leaves based on a mechanistic representation involving biochemical equations of leaf photosynthesis, regulated in part by atmospheric CO_2 concentration, leaf temperature, and photosynthetic capacity as defined by the maximum rate of carboxylation (V_{max}) and the electron transport rate [2]. V_{max} describes photosynthesis limitation by the photosynthetic Rubisco enzyme system, which is the dominant control at light saturation, whereas the electron transport rate becomes limiting at subsaturating light intensities. The specification of V_{max} is critical and substantially contributes to the overall uncertainties of model predicted carbon fluxes [3]. V_{max} is a leaf-level parameter that cannot be measured directly but must be inferred from leaf gas exchange measurements, which makes it difficult to prescribe on a global scale. As a result, models typically use fixed values for broad categories of vegetation types although in reality temporal and spatial variability can be significant [4]. V_{max} is directly related to the Rubisco enzyme that acts as a catalyst for carbon fixation within the leaf chloroplast. Rubisco in turn is strongly related to the nitrogen content of leaves (N) because of the large proportion of N in the photosynthetic machinery [5]. At the same time, since chlorophylls are vital pigments for photosynthesis, strong correlations have been reported between leaf chlorophyll (Chl) and N [6]. The use of Chl as a proxy is more convenient as it directly controls leaf absorption in the visible waveband region and therefore may be retrieved from satellite observed reflectances by inversion of leaf optics and canopy reflectance models.

However, retrieving Chl from space observations is not a trivial task, due to the interference of atmospheric effects, canopy structure, and soil background in addition to the ill-posed nature of model inversion. The physically-based REGularized canopy reFLECtance model (REGFLEC; www.regflec.com) was developed in an effort to better control these confounding factors [7]. REGFLEC combines leaf optics, canopy reflectance, and atmospheric radiative transfer modules, and has demonstrated ability to retrieve Chl from at-sensor radiance observations with acceptable accuracy in agricultural systems (10-20%) [7].

In this study, estimates of Chl are translated into V_{max} based on semi-mechanistic formulations parameterized based on compiled data from experimental studies. The resulting relationships are embedded within the photosynthesis scheme of the Community Land Model (CLM4, http://www.cesm.ucar.edu/models/ccsm4.0/clm/), thereby bypassing the use of fixed PFT specific V_{max} values. The effect of the updated V_{max} parameterization on simulated water and carbon fluxes is evaluated over different land cover types using REGFLEC derived Chl data.

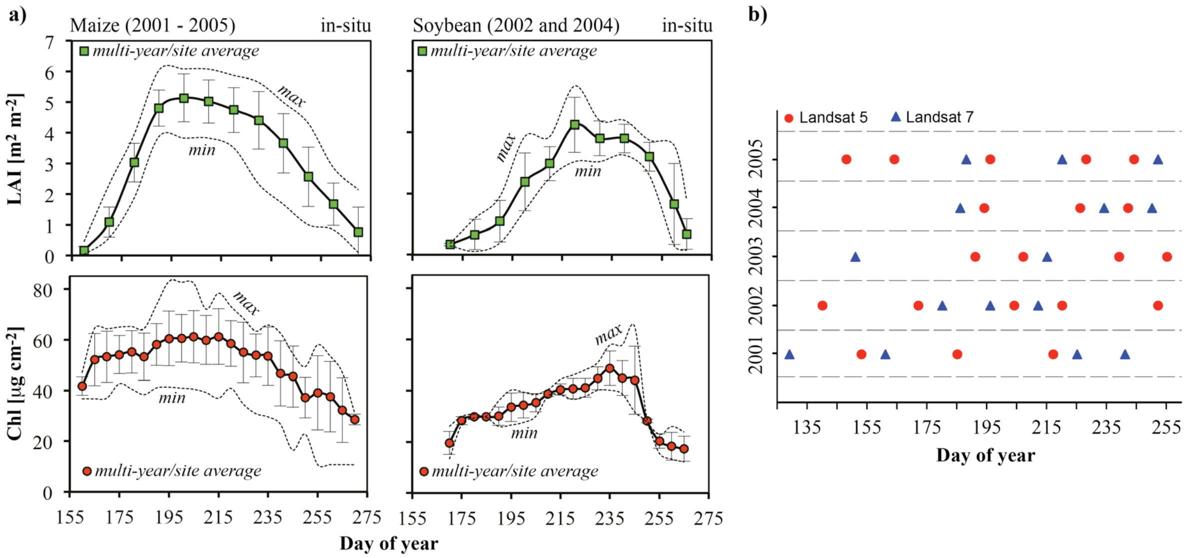

Fig. 1 a) Averged time-series of measured LAI and Chl for maize and soybean fields at Mead, Nebraska, displaying intra and inter-field variability over a five year period (2001 – 2005). b) Timing and frequency of acquired Landsat scenes at Mead, NE over the 2001 – 2005 study period. These were input to REGFLEC for Chl retrieval.

2. METHODS

2.1. Community Land Model

Exchanges of water and carbon are simulated using the Community Land Model (CLM, http://www.cesm.ucar.edu/models/cesm1.0/clm/), which is the land component used in the Community Earth System Model (CESM). CLM4 simulates CO_2 uptake by the canopy using a coupled photosynthesis-stomatal conductance model based on biochemical equations of leaf photosynthesis [2] and a semi-empirical model of stomatal functioning [8]. V_{max} is derived as a function of mass-based leaf N concentration and specific leaf area defined for each plant-functional type (PFT). The CLM4 also includes a carbon-nitrogen (CN) model for a fully prognostic treatment of the terrestrial carbon and nitrogen cycles. The CN biogeochemistry model diagnoses the amount of N available for photosynthesis, which is used to downregulate the potential gross primary productivity (GPP) calculated from the leaf photosynthetic rate without N constraint. The work described here employs the CLM4 satellite phenology version (CLM4-SP) where vegetation inputs are prescribed (e.g. from satellite data) rather than prognosed. In CLM4-SP the potential GPP is reduced by multiplying V_{max} with a PFT-specific factor (0-1) that represent N constraint on GPP. This mechanism is bypassed here by using satellite estimates of Chl directly to derive V_{max} in the spatial and temporal domain, assumed to better reflect given environmental and physiological conditions.

2.2. Regularized canopy reflectance model (REGFLEC)

REGFLEC [7, www.regflec.com] represents an automated and image-based methodology for translating at-sensor radiance observations from multi-spectral sensors like Landsat into maps of leaf chlorophyll (Chl) and leaf area index. REGFLEC combines an atmospheric radiative transfer model (6SV1), a canopy radiative transfer model (ACRM or SAIL), and a leaf optical properties model (PROSPECT), and was developed in an effort to better control the confounding influence of atmospheric effects, leaf and canopy characteristics and soil background on retrieved biophysical properties. The tool is freely distributed on the REGFLEC webpage and can be directly applied to most regions through a user-friendly GUI. Recent refinements include 1) automated preparation of Landsat time-series data (including scene resizing, cloud detection and land cover classification), 2) automatic download and on-the-fly processing of atmospheric state data from multiple satellite (e.g. Terra and Aqua MODIS, AIRS, OMI, TOMS) and ground-based (e.g. AERONET) sources, and 3) an option to use downscaled MODIS LAI to constrain the inverse vegetation retrieval process. A detailed description of the basics behind the REGFLEC Look-Up-Table (LUT) based inversion approach is given in Refs. [7] and [9].

2.2. V_{max} – Chl relationship

A mechanistic approach for linking Chl to the maximum rate of carboxylation at 25 °C (V_{max25}) is described in detail in Ref. [9]. V_{max} is directly related to the RuBisCO enzyme that acts as a catalyst for carbon fixation within the leaf chloroplast. RuBisCO in turn is strongly correlated to leaf N that typically exhibits a significant linear relationship to Chl [5,6]. Accordingly

$$V_{\max}^{25} = c_0 \cdot K_{cat}^{25} \cdot F_{LNR} \cdot N = c_0 \cdot K_{cat}^{25} \cdot F_{LNR} \cdot \left(a \cdot Chl + b\right) \qquad \text{Eq. 1}$$

where F_{LNR} is the fraction of N in RuBisCO, K_{cat}^{25} is the RuBisCO turnover rate, c_0 is a conversion constant and *a* and *b* are linear regression coefficients. Representative parameterizations for F_{LNR}, K_{cat}^{25}, and the linear regression coefficients were established based on a literature survey [9]. The resulting relationships provide a convenient mechanism for translating satellite estimates of Chl into V_{max} for integration into the photosynthesis scheme of CLM4.

2.2. In-situ and satellite data

LAI and Chl measurements from three sites (Ne1, Ne2, Ne3), located at the University of Nebraska-Lincoln Agricultural Research and Development Center near Mead, Nebraska, was used in this study. The three sites are all approximately 65-ha fields located within 1.6 km of each other. Ne1 has been continuously under maize since 2001 whereas Ne2 and Ne3 are under a maize-soybean rotation. Ne1 and Ne2 are both irrigated with a center pivot system, whereas Ne3 relies entirely on rainfall for soil moisture. Green LAI was determined from destructive samples at approximately 10 to 14-day intervals covering all phenological stages (Fig. 1a). Chl was estimated non-destructively using reflectance measurements [10] and collected approximately twice a week during the growing seasons of 2001 to 2005 (Fig. 1a).

A total of 35 predominantly clear Landsat-5 TM and Landsat-7 ETM+ images (Fig. 1b) were acquired over the study period from the USGS EarthExplorer (http://earthexplorer.usgs.gov). The image digital counts were input to REGFLEC for further processing. For each year, the total number of scenes were first automatically co-registered and resized and corrected for cloud contamination, and image files with at-sensor radiance data in 4 Landsat bands (blue, green, red and near-infrared) were prepared for use in REGFLEC. To facilitate vegetation parameter retrievals using SAIL-PROSPECT, REGFLEC atmospherically corrected each scene individually using spatially distributed information on aerosol optical thickness from the Terra MODIS aerosol product (MOD04, 10 km), total precipitable water from the Terra MODIS near-infrared derived product (MOD05, 1 km), and total ozone from either the Total Ozone Mapping Spectrometer (TOMS) (2001-2003) or the Aura Ozone Monitoring Instrument (OMI) (2004 and 2005). Aerosol size distribution was retrieved from the Konza EDC AERONET site, which is located ~250 km south of Mead and assumed to represent aerosol type conditions at Mead

3. RESULTS

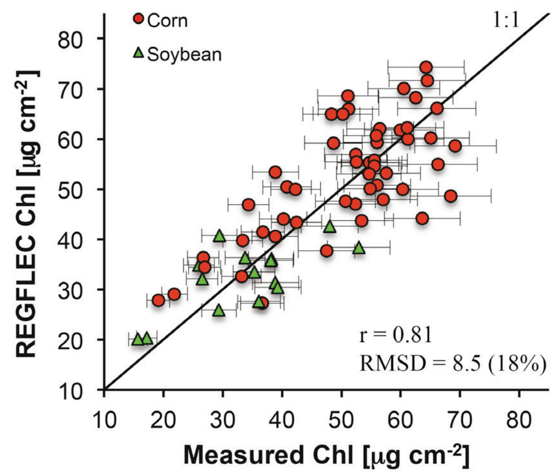

Fig. 2 Validation of REGFLEC leaf chlorophyll (Chl) retrievals against in-situ measured data from irrigated and rainfed agricultural fields over a 5 year period.

3.1. Validation of REGFLEC retrievals

Fig. 2 compares REGFLEC retrieved Chl (using Landsat) against in-situ observations over a 5 year period (2001 - 2005) encompassing different development stages (green-up, reproductive, senescence) of corn and soybean (Fig. 1a). REGFLEC predicts higher values of Chl for corn (56±7 µg cm^{-2}) than for soybean (34±7 µg cm^{-2}) during green-up and reproduction, which is consistent with the in-situ measurements (57±10 µg cm^{-2} and 36±8 µg cm^{-2}, respectively) (Fig. 1a). The overall performance of REGFLEC in reproducing the dynamics of in-situ measured Chl is characterized by a Pearson's correlation coefficient (r) of 0.81, and a root-mean-square deviation (RMSD) of 8.5 µg cm^{-2}, which amounts to a relative RMSD of 18 % (Fig. 2).

3.12. Constraining modeled fluxes using Chl

In this study, single-point simulations of GPP (and ET) were performed using the CLM (Section 2.1) forced with tower-based meteorology (incoming solar radiation, air temperature and humidity, wind speed, precipitation, surface pressure) and in situ based LAI. Tower flux observations were acquired from two irrigated fields and one rainfed field. The REGFLEC generated Chl time-series were translated into V_{max} using Eq. 1. CLM was then executed 1) in default mode using a fixed PFT-specific V_{max} value (57 µmol m^{-2} s^{-1}) and 2) using the Chl constrained V_{max} values. Fig. 3 compares hourly observations of GPP from all sites and years against simulated values using a fixed V_{max} (Fig. 3a) and a V_{max} prescribed by satellite derived Chl (Fig. 3b), and clearly the scatter and bias are significantly reduced when introducing a Chl constraint on GPP. Changes in V_{max} indirectly affect transpiration through stomatal conductance

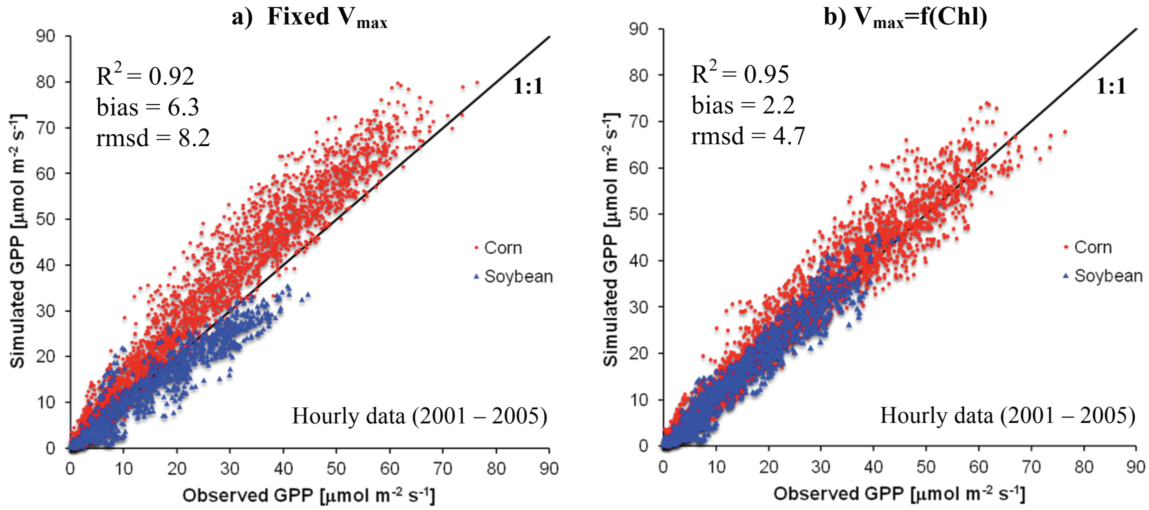

Fig. 3 Hourly observations of gross primary productivity (GPP) over corn and soybean plotted against simulations (CLM4) that used a fixed V_{max} (a) and a V_{max} prescribed by leaf chlorophyll (b) retrieved from Landsat imagery. Standard statistical metrics are indicated on the plots.

and the imposed Chl constraint was also seen to reduce biases in simulated water fluxes (not shown).

4. CONCLUSION

The results suggest that Chl holds useful information on the magnitude and seasonal variability in leaf photosynthetic capacity, advocating the potential of satellite retrieved Chl for constraining simulations of water and carbon fluxes in space and time using generalized relationships between V_{max} and Chl. Much relies on the ability to retrieve Chl accurately from remote sensing data, which remains extremely challenging given limited information carried by the radiometric signal. While REGFLEC was able to retrieve Chl fairly accurately, research is still needed to properly separate the relatively week leaf signal from the total remote sensing signal that incorporates confounding contributions from the atmosphere, canopy and background. Future applications of REGFLEC will focus on implementing additional spectral bands in order to increase the amount of information used in the inversion process.

5. REFERENCES

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