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Advances in remote sensing of vegetation function and traits

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ABSTRACT

Remote sensing of vegetation function and traits has advanced significantly over the past half-century in the capacity to retrieve useful plant biochemical, physiological and structural quantities across a range of spatial and temporal scales. However, the translation of remote sensing signals into meaningful descriptors of vegetation function and traits is still associated with large uncertainties due to complex interactions between leaf, canopy, and atmospheric mediums, and significant challenges in the treatment of confounding factors in spectrum-trait relations. This editorial provides (1) a background on major advances in the remote sensing of vegetation, (2) a detailed timeline and description of relevant historical and planned satellite missions, and (3) an outline of remaining challenges, upcoming opportunities and key research objectives to be tackled. The introduction sets the stage for thirteen Special Issue papers here that focus on novel approaches for exploiting current and future advancements in remote sensor technologies. The described enhancements in spectral, spatial and temporal resolution and radiometric performance provide exciting opportunities to significantly advance the ability to accurately monitor and model the state and function of vegetation canopies at multiple scales on a timely basis.

1. Introduction

Studies on the applications of remote sensing for characterizing vegetation canopies started accelerating in the late 1960’s (Fig. 1) with a cornerstone publication on spectral signatures and effects of physical mechanisms and physiological stress on the spectral reflectance of leaves and canopies (Knipling, 1970). Challenges in the interpretation of remotely sensed canopy reflectance and understanding effects of causative factors such as leaf area, background reflectance, shadows, leaf orientation, and viewing and illumination geometry were also recognized at an early stage (Colwell, 1974). Treatment of confounding factors in spectrum-trait relations still represent a substantial complication for advancing the significance and utility of remote sensing data.

The launch of the Landsat (ERTS-1) mission in 1972 (Fig. 2) initiated investigations on its capability for vegetation monitoring and categorization. Pioneering work by Tucker (1979) helped develop the Normalized Difference Vegetation Index (NDVI), which quickly became the most dominant satellite observable metric for plant biomass and photosynthetic activity and spatio-temporal changes thereof (Myneni et al., 1997; Tucker et al., 1985). While strong empirical correlations between NDVI and vegetation biomass generally exist across broad gradients, fine scale discrimination depends on a multitude of site and plant specific factors, which reduces generality and reproducibility in time and space. The desire to improve the interpretation of vegetation reflectance and vegetation indices led to important developments in canopy radiative transfer modeling such as the Scattering by Arbitrary Inclined Leaves (SAIL) model (Verhoef, 1984), now in widespread use as a fundamental basis for the retrieval of vegetation biophysical characteristics from remotely sensed data. The increasing evidence and understanding of correlations between leaf reflectance and biochemical concentrations also encouraged retrieval of foliar biochemistry (e.g., chlorophyll) from remote sensing spectra, to be used as valuable indicators of plant productivity and nutrients availability in space and time (Curran, 1989). This fostered the development of fully integrated leaf and canopy reflectance models such as PROSAIL (Baret et al., 1992) that simulates the canopy reflectance field using leaf reflectance and transmittance spectra from the PROSPECT (Jacquemoud and Baret, 1990) leaf optical properties model. This important development facilitated the estimation of key photosynthetic pigments directly from canopy reflectance spectra based on model inversion. There is also development in the understanding of plant photosynthetic activity through physical models utilizing plant fluorescence (Van der Tol et al., 2009). Observations of solar-induced chlorophyll fluorescence represent an exciting opportunity to directly assess photosynthetic activity and detect vegetation stress before chlorophyll or leaf reductions take place. These relatively new spaceborne measurements have recently come to light from GOME-2, GOSAT, and OCO-2. The European Space Agency is developing the dedicated Fluorescence Explorer (FLEX) concept mission, which, in tandem with Sentinel-3 (Fig. 2), could further advance this line of research.

Multi-spectral imaging instruments from the early 1990’s, such as Landsat TM and SPOT HRV, recorded radiance in a few broad spectral bands across the visible, near-infrared and shortwave

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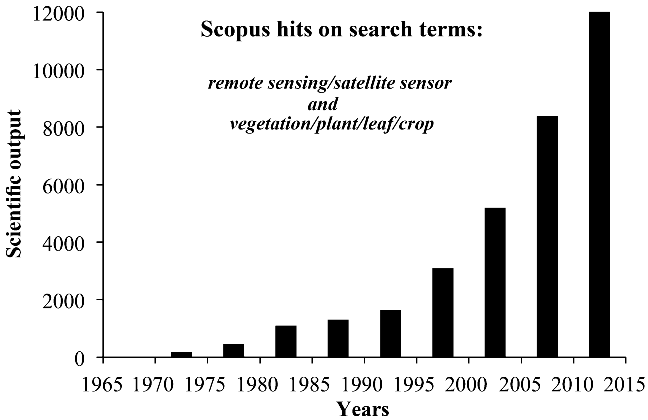

Fig. 1. Number of scientific publications over 5-year periods during the period 1965–2015 based on a Scopus search on ((‘remote sensing’ or ‘satellite sensor’) and (‘vegetation’ or ‘plant’ or ‘leaf’ or ‘crop’)).

infrared domain (Fig. 2). The limited spectral detail of available sensors combined with large uncertainties in atmospheric correction (i.e., conversion of sensor radiances to surface bidirectional reflectances), negatively affected the utility of physically based methods for the retrieval of leaf biochemistry. Developments in hyperspectral imaging (Goetz et al., 1985) led to enhancements in radiometric information content with data acquisition in many narrow (<10 nm) contiguous bands over a selected wavelength interval, and improved capacity for characterizing vegetation type, health and function. Hyperspectral sensing (image spectroscopy) has played a key role in identifying functional links between physiological processes and narrow-band spectral reflectance features such as the correlation of red-edge information with chlorophyll content (i.e., a key proxy for vegetation productivity) (Curran et al., 1990) and the strong association of the Photochemical Reflectance Index (PRI) with short-term changes in photosynthetic efficiency based on the normalized difference between leaf reflectance at 531 nm and a reference wavelength (~550 nm) (Gamon et al., 1992). Insights from ground-based hyperspectral analyses have also proven invaluable for the development of remote sensing methods and optimal sensor designs and multi-spectral band designations. However, the potential to assess leaf level traits and function from the composite surface signal of remote sensors is significantly challenged by obfuscating factors introduced by the canopy and atmospheric mediums.

Radiative transfer models provide an explicit physical connection between the observed remote sensing signal and the target variable (e.g., vegetation trait). The development and application of physically sound integrated models to reliably quantify and discriminate between the atmospheric, soil, canopy and leaf contribution to reflected electromagnetic radiation is central for advancing the field. However the inversion of models to retrieve vegetation characteristics from canopy reflectance observations is affected by the ill-posed inverse problem (Combal et al., 2002), which causes different model parameter solutions to produce almost identical spectra. Regularization strategies are necessary to improve the robustness and accuracy of retrieved properties, and can involve the use of (1) prior information, (2) enhanced information content in the form of e.g., additional spectral bands, and

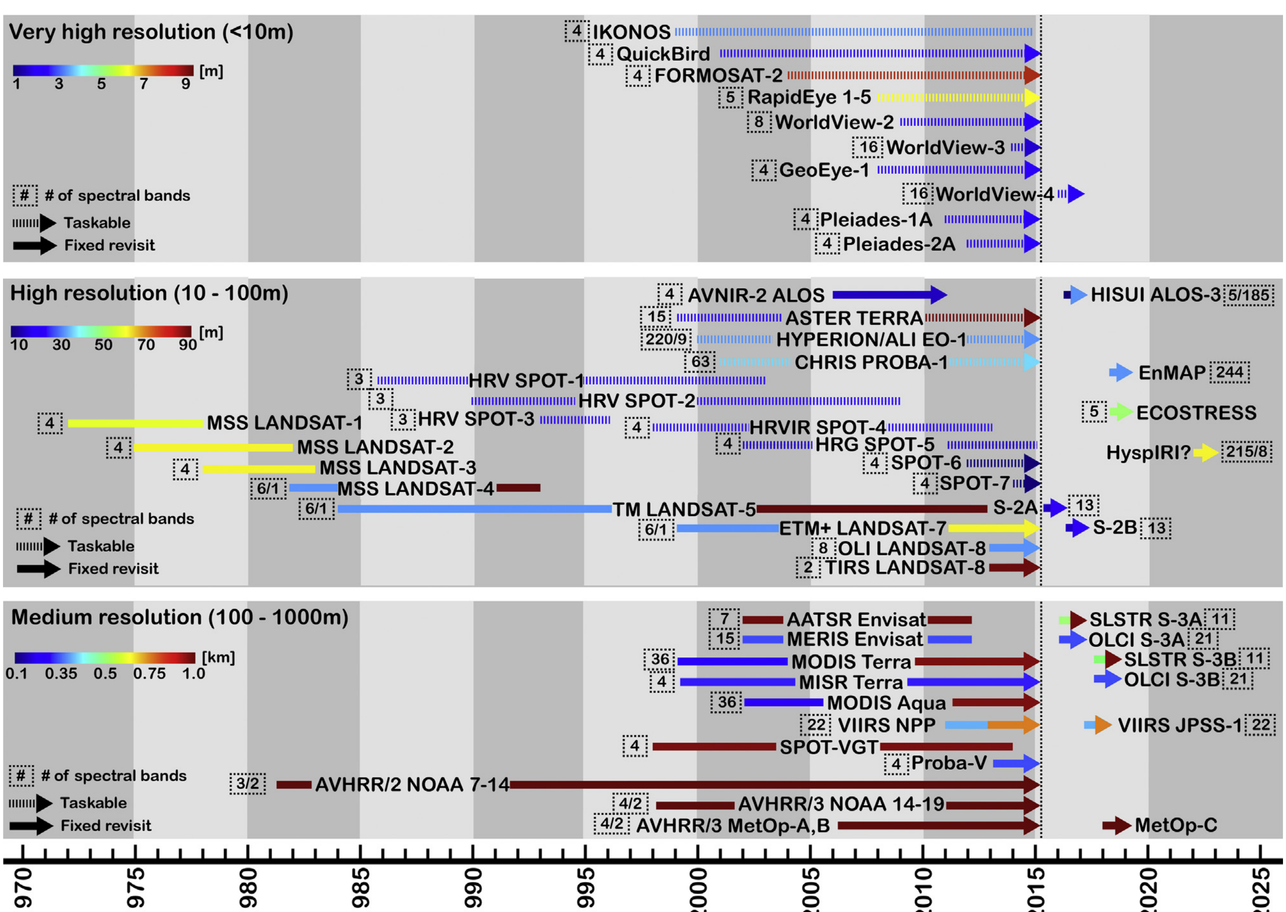

Fig. 2. Timelines of historical and planned multi- and hyperspectral optical and thermal satellite sensors relevant for remote sensing of vegetation at medium to very high spatial resolution. (For interpretation of the references to colour in the text legend, the reader is referred to the web version of this article.)

multi-angular and multi-sensor data streams, (3) constraints based on temporal and spatial features in the observations, and (4) assimilation of empirical data to continuously improve model accuracy. The development of novel regularization strategies to effectively constrain the inversion process while maintaining sufficient physical realism, continue to be an area of active research. An important prerequisite is the availability of highly accurate (i.e., atmospherically corrected) remote observations of the surface reflectance field.

Significant advances in sensor design and radiometric and biophysical performance boosted a new era in Earth Observation around the change of the millennium with the appearance of spectrally, spatially and temporally enhanced medium resolution sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and the Medium Resolution Imaging Spectrometer (MERIS) on Envisat (Fig. 2). With several new (and narrower) bands in critical segments of the electromagnetic spectrum, the potential to globally map spatio-temporal variations in vegetation biophysical, physiological and structural quantities greatly increased as reflected in a parallel exponential rise in scientific output (Fig. 1). While Envisat is no longer operational, data continuity is ensured with the awaited launch of Sentinel-3 in 2016. The Visible Infrared Imaging Radiometer Suite (VIIRS), currently on the Suomi National Polar-orbiting Partnership (NPP) bridge mission, builds on MODIS and Advanced Very high Resolution Radiometer (AVHRR) heritage and will be one of several instruments onboard the Joint Polar Satellite System (JPSS) to ensure continuity of MODIS-like observations into the future (Fig. 2).

The Earth Observing-1 (EO-1) mission for testing and validating new sensor designs included the first spaceborne hyperspectral sensor (Hyperion), which can be tasked to observe targeted areas in narrow swaths (~7.5 km) at 30 m resolution, and currently remains in operation. Still the need for an operational hyperspectral mission to produce repeatable high resolution images for all terrestrial ecosystems has not been fulfilled. However the planned launch of the Hyperspectral Imager Suite (HISUI) onboard ALOS-3 in 2016, the Environmental Mapping and Analysis Program (EnMAP; www.enmap.org) in 2018 and, if funded, the Hyperspectral Infrared Imager (HyspIRI; hyspiri.jpl.nasa.gov) around 2022, constitute a hyperspectral revolution with far reaching opportunities.

High resolution thermal infrared (TIR) data have been acquired continuously by Landsat since 1984 but the true value of thermal information for remote sensing of vegetation state and function remains to be fully realized such as through spaceborne hyperspectral scanners in the thermal part of the electromagnetic spectrum. Thermal sensing is particularly sensitive to stomatal behavior, as canopy temperatures will respond directly to water stress through induced stomatal closure and decreased evaporative cooling. Thus TIR observations can provide valuable indications of stress conditions occurring at much shorter time-scales than those reflected in typically more gradual pigment reductions observable by optical spectral sensing. The development of techniques to effectively exploit synergies across the full visible to shortwave infrared (VSWIR) to TIR spectrum is seen as an important and required innovation toward improved characterization of vegetation health and function in space and time domains. The proposed HyspIRI mission will also carry a multi-spectral TIR instrument, in addition to the hyperspectral measurements. Preceding HyspIRI, the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS; ecostress.jpl.nasa.gov), scheduled for 2017, will provide high resolution (~50 m) reconstructed diurnal monitoring of surface temperature and associated evapotranspiration products with a 4-day repeat cycle.

The era of commercially available very high resolution (<10 m) programmable multi-spectral satellite sensor systems was initiated with the Launch of IKONOS in 1999 (Fig. 2). This advent facilitated the targeted and potentially frequent monitoring with a few multispectral standard bands (i.e,. blue, green, red, near-infrared) enabling NDVI-based studies of vegetation state. RapidEye (2008-) was the first commercial sensor to also include a band in the red-edge, recognized as key for improving chlorophyll retrieval capabilities. The WorldView series of satellites (2009-) provided further enhancements to spectral monitoring with 8 multispectral bands (incl. red-edge) at very high spatial resolutions (~1.25–2.0 m) in addition to 8 SWIR bands (WorldView-3). Despite extremely well-equipped sensor designs and capabilities, their potential for precision vegetation characterization and monitoring has yet to be fully realized due to prohibitively expensive image acquisition costs. This highlights the gap that currently exists between expensive commercial and operational (with free data distribution policy) systems in terms of their spatial detail and utility in applications such as precision agriculture – a critically important application remote sensing field, which remains actively researched to this day with the full potential still to be realized. The pair of Sentinel-2 satellites (S-2A, S-2B), with S-2A scheduled to launch this month, will bridge this gap by delivering narrower band multispectral data (including 2 narrow bands in the red-edge) at resolutions down to 10 m with a 2–5 days revisit (once both satellites are in orbit), with the opportunity to significantly advance the ability to monitor the state and function of vegetation routinely and globally at no cost through enhanced definition of the red-edge.

Airborne remote sensing has been an active research field for many years with a notable service of the hyperspectral Airborne Visible Infrared Imaging Spectrometer (AVIRIS) since 1987, which has enabled studies not feasible by the means of satellite Earth observation data. Airborne sensing has also been instrumental in proving new sensor technologies, and most satellite sensors have been preceded by an airborne equivalent. Unmanned Aerial Vehicles (UAVs) are affordable, can be operated autonomously and represent an emerging field in airborne sensing that has the potential to extend and evolve Earth observing disciplines, including exciting opportunities in the context of precision agriculture (Zarco-Tejada et al., 2012). In contrast to single-source satellite imagery, these systems are not limited by space and time constraints and meet the critical requirements of optimum resolution and radiometric information content (such as the ability to collect co-registered hyperspectral and thermal data), which makes them ideally suited for identifying within-field variations in vegetation health and condition resulting from non-optimal growing conditions. The enhanced cm-scale spatial detail can improve the separation of soil and canopy contributions and reduce obfuscating effects of soil background, structure, and shadow (i.e., by isolating pure vegetation signals), providing an improved capacity to remotely sense and model vegetation traits and function.

We are at the brink of a new era of Earth observation for vegetation monitoring. Enhancements in spectral, spatial and temporal resolution and radiometric performance provide the foundation to significantly advance the characterization of vegetation type, condition and function across multiple space and time scales. However, optimal exploitation of current and future advancements in remote sensor technologies, as detailed in this Special Issue, requires directed research toward:

a Developing extendable, well-constrained and physically realistic integrated (leaf–canopy) radiative transfer models for application over a diversity of cover types and environments, with the ability to robustly assess and discriminate canopy biochemistry, structure and biomass (Atzberger et al., 2015).
b Adaptation of retrieval algorithms to take advantage of cross-sensor synergies and the enhanced spectral, spatial and temporal capabilities of current and planned satellite sensor systems (Ramoelo et al., 2015; Nag et al., 2015; Sawada et al., 2015)

c Improving the treatment of confounding factors in spectrum-trait relations and developing enhanced regularization strategies, to effectively constrain the inverse estimation of vegetation properties from Earth observations while maintaining sufficient realism in model physics (Zurita-Milla et al., 2015; Nikopensius et al., 2015).
d Combining thermal and spectral sensing for improved identification of foliar chemistry, plant stress, physiological limitations and photosynthetic function occurring over different time scales (Elarab et al., 2015)
e Identifying new and novel uses of the vast information content present in hyperspectral data streams (Kokaly and Skidmore, 2015; Roelofsen et al., 2015).
f Linking remote sensor retrieved vegetation traits to vegetation functional behavior (e.g., photosynthetic capacity, stomatal conductance) and integration into process models as observational constraints (Musavi et al., 2015; Huesca et al., 2015; Houborg et al., 2015; Machwitz et al., 2015)
g Developing the science to fully exploit advances made in UAV sensor technology.

2. The special issue

This special issue includes a compilation of 13 papers each addressing unique aspects in the advancement of remote sensing of vegetation function and traits, which can be grouped into two themes: (1) Remote sensing based estimation and monitoring of plant biophysical and biochemical traits; and, (2) Linking of vegetation properties to function and integration into models. Eight papers address the first theme. Zurita-Milla et al. (2015) visualize the ill-posedness of model inversion using a novel concept based on Self-Organizing Maps (SOM). SOM represent a machine learning algorithm used here to effectively convey, in 2 dimensional space, the degree of ill-posedness of different biophysical and biochemical characteristics retrieved from model inversion of simulated reflectance spectra matching the spectral configuration of soon-to-be launched Sentinel-2. The characteristics of patterns and variability in these maps provide a mechanism for evaluating the uncertainties of retrieved parameters. While variables such as leaf area index (LAI), leaf chlorophyll and water content are generally found to be less ill-posed, furthering the integration of spatial and temporal regularization constraints is needed to more effectively cope with the ill-posed inverse problem.

Atzberger et al. (2015) illustrate important advantages and drawbacks of physical and empirical methods for grassland LAI retrieval from airborne hyperspectral data. It is shown that a lookup table inversion of PROSAIL using hyperspectral bands selected on the basis of a recursive band elimination scheme produces retrieval accuracies comparable to statistical methods employing in-situ calibrated vegetation index relationships. Statistical methods are simple and straightforward but require a sufficiently large and representative calibration database and may lack generalization and reproducibility. Physical methods are intrinsically more generic and transferable but retrieval accuracies will depend on the employed inversion procedure, model parameterization, and the suitability of the model for the studied vegetation types.

UAVs facilitate enhanced monitoring with time-critical account of fine-scale variations in plant health and function. The retrieval of cm-scale chlorophyll content from thermal and multi-spectral optical imagery collected by an unmanned aerial system is the objective in Elarab et al. (2015). A complex statistical regression model (i.e., Bayesian relevance vector machine) is trained on a dataset of in-situ collected leaf chlorophyll measurements and the machine learning algorithm intelligently selects the most appropriate bands and indices for building regressions with the highest prediction accuracy. Interestingly, thermal band data is shown to be a significant contributor in the chlorophyll prediction models, which suggests important synergies of data in the visible to near-infrared and thermal domain for the estimation of plant pigments closely linked to leaf nitrogen and productivity.

In preparation for the enhanced spectral, spatial and temporal capabilities of Sentinel-2, Ramoelo et al. (2015) attempts to retrieve leaf nitrogen and biomass directly, taking advantage of red-edge band information provided by WorldView-2 at 2 m resolution. The predictive power of a random forest machine learning technique for leaf nitrogen estimation is shown to benefit from the inclusion of red-edge bands, due to enhanced sensitivity to chlorophyll variations and reduced sensitivity to background effects. The derived properties are important proxies for rangeland quality and quantity.

Plant phenolics represent a significantly less studied biochemical constituent in a remote sensing context, although phenolic concentration may contribute to the assessment of vegetation stress and species discrimination. Kokaly and Skidmore (2015) investigate the utility of spectroscopy to characterize and quantify plant phenolics, and detect a unique absorption feature near 1.66 μ in spectra of leaves and plants. Since the major plant biochemical constituents do not confound this feature it has potential as a direct indicator of the presence of phenolic compounds, as successfully demonstrated using tea leaf and canopy spectra.

Reflectance spectra acquired over forest canopies combine understory and overstory contributions, which can easily confound the extraction of biophysical and biochemical properties. Nikopensius et al. (2015) documents measured spectral reflectance patterns and dynamics of common understory types in mature hemi-boreal forests. A high degree of variability is observed in the spectral properties of the studied understory layers, which complicates the application and parameterization of forest reflectance models. The collected datasets are useful for quantifying the role of forest understory in radiative transfer simulations and for the interpretation of remotely sensed reflectance spectra.

Forest structure is also the topic in Sawada et al. (2015) who deals with the retrieval of forest canopy height from spaceborne LiDAR. An extension of the SOM machine learning method is adopted for building a rule-based system of input/output relationships linking a suite of explanatory MODIS dataset components with observed canopy height for continuous spatial modeling of canopy height in Amazon forest at 500 m resolution. The robustness of the developed canopy height map is evaluated against independent ground-based and satellite-based sources and the map may have important applications in forest management and carbon budget accounting in the region.

Nag et al. (2015) proposes a novel constellation of small satellites in formation flight to make multi-spectral near-simultaneous samplings of a target footprint at multiple angles. This type of information is beneficial for characterizing the Bidirectional Reflectance-Distribution Function (BRDF) and the anisotropy of the vegetation surface, needed for example for accurate derivation of surface reflectance products and vegetation structure. Current spaceborne mission instruments provide inadequate data for estimating global BRDF, and a 6-satellite formation would serve as an important complement to flagship missions to reduce current sampling gaps.

The remaining five contributions encompass conceptual frameworks for better defining ecosystem functional behavior and the integration of plant traits and biophysical characteristics into models for improved monitoring of ecosystem processes and function in space and time. Musavi et al. (2015) introduces the concept of ecosystem functional properties (EFPs), which represent observable proxies for the ecosystem functional state, and proposes a novel conceptual framework for linking EFPs to plant traits and ecosystem vegetation properties measured in-situ or remotely. Challenges and uncertainties are discussed and the utility and perspective of remote sensing to inform the process is thoroughly reviewed.

A related concept of optically distinguishable functional types (i.e., "optical types") is adapted in Huesca et al. (2015) to more closely link remote sensing data with ecosystem dynamics. In this work the "optical types" concept is implemented on the basis of MODIS NDVI time-series dynamics over a Mediterranean broadleaf forest region. Autocorrelation in NDVI time-series data is used to identify/define distinct optical types within the forest, which are more effective at assessing forest dynamics and diversity in a quantitative and comprehensive way given the high level of agreement that exists between temporal autocorrelation and phenometrics.

Roelofsen et al. (2015) links airborne hyperspectral reflectance measurements and ancillary topographic variables to site factors (soil acidity and groundwater water level) through so-called plant indicator values (IVs). IVs are continuous numerical values typically derived from expert judgment in order to synthesize plant properties and physiology into a single number. A multi-linear regression technique is used to derive predictive models for IV estimation using a training dataset of observed IVs and reflectance spectra and topographical data as explanatory variables. The IVs are then translated into site factors based on existing empirical relationships. While the remote sensing approach is associated with significant uncertainties, integrated with other sources it has the ability to improve spatially distributed ecological modeling, management and assessment.

In alignment with the concept outlined in Musavi et al. (2015), Houborg et al. (2015) establishes semi-mechanistic inter-linkages between leaf chlorophyll content and leaf photosynthetic capacity ($V_{\max}$) for important agricultural crops. Subsequently, a leaf chlorophyll constrained version of the Community Land Model is developed, thereby bypassing the questionable use of temporally invariant and broadly defined plant functional type specific $V_{\max}$ values. Validation of simulated Gross Primary Productivity (GPP) against flux tower observation demonstrates the utility of leaf chlorophyll as a model constraint, and supports the candidacy of satellite retrieved leaf chlorophyll as an observational proxy for $V_{\max}$. The development of an observationally driven scheme for constraining $V_{\max}$ in space and time is seen as a necessary step toward reducing uncertainties in model predicted GPP across seasons, years and plant communities.

Reducing errors in the estimation of GPP is also the objective in Machwitz et al. (2015), targeting a region in West Africa with a distinct precipitation gradient. The adaptation of a regional light use efficiency-based biomass model to the 250 m scale based on spatially enhanced and gap-filled MODIS data produces reasonable agreement with available flux tower data. Overall estimation accuracies are in line with results of other studies but the enhanced spatial resolution and data coverage allow for improved differentiation of vegetation growth forms such as woody and herbaceous vegetation.

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Rasmus Houborg*
Joshua B. Fisher
Andrew K. Skidmore
Biological and Environmental Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Saudi Arabia
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA, 91109, USA
Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, Hengelosestraat 99, 7500 AA Enschede, The Netherlands

* Corresponding author.
E-mail address: Rasmus.houborg@kaust.edu.sa (R. Houborg)

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