Imaging Spectroscopy of Vegetation Photosynthetic Activity

Zbyněk Malenovský [a,*], Michael E. Schaepman [a,b], Alexander Damm [a], and Felix Morsdorf [a]

[a] *Remote Sensing Laboratories, University of Zürich, Switzerland*
[b] *Centre for Geo-Information, Wageningen University, The Netherlands*
[*] *Correspnding author: Winterthurerstrasse 190, CH-8057 Zürich, Switzerland, zbynek.malenovsky@geo.uzh.ch, http://www.geo.uzh.ch/rsl*

Abstract

Photosynthesis is an oxygenic bio-chemical reaction, when molecules of CO_2 and H_2O with energy of photons absorbed between 400-700 nm are transformed into the high-energy carbohydrate macromolecules and O_2 molecules. Green plants are creating, through their ability to carry on photosynthesis, an immeasurably large and continuously replenishable source of energy and material for a sustainable life on the Earth. Therefore, a global Earth observing system for monitoring of photosynthetic processes and vegetation primary production is one of the most important aims of the remote sensing science, especially in the era of global climate change. Photosynthetic processes are carried out at the thylakoid membranes of the leaf chloroplasts, involving the photosynthetically active foliage pigments (mainly chlorophyll a+b; Cab), while optical remote sensing is measuring modification in the electromagnetic radiation reflected by the Earth surfaces (e.g., vegetation canopy) as the function of wavelength, observation and illumination geometries, spatial extent, polarization, and time. Obviously, scaling of the optical photosynthetic indicators from leaf up to structurally heterogeneous canopy (airborne and/or satellite) observations represents a scientific challenge to be solved.

Vegetation reflectance measurements of broad band satellite spectroradiometers (e.g., LANDSAT-7, SPOT-4, 5, etc.) allow computation of the broad-band Normalized Difference Vegetation Index (NDVI; Rouse et al., 1973) that was designed to distinguish photosynthetically active vegetation from the bare soil, snow or water surface on the ground. Early research suggested a close statistical relationship between the NDVI and the green Leaf Area Index (LAI) (Tucker, 1979) of vegetation, indicating the canopy assimilatory capacity. On the other hand several recent studies reported low correlation of these two variables in dense canopies (Wang et al., 2005). Modern imaging spectroscopy methods are using the physical based radiative transfer models to retrieve LAI and FPAR (Fraction of absorbed Photosynthetically Active Radiation) of specific biome vegetation types from optical satellite image data (e.g., MODIS Aqua and Terra LAI/FPAR product MOD15; Myneni et al., 2002). Similar mechanistic approach can be applied to estimate content of various leaf biochemical compounds, e.g. photosynthetically active chlorophyll Cab pigments (Lukeš et al., 2009), indicating actual state and stress load of vegetation.

Massive efforts were undertaken to use optical remote sensing data for the estimation of vegetation carbon assimilation, i.e. Gross Primary Productivity (GPP), and, subsequently after removal of carbon released by plants via respiration, Net Primary Productivity (NPP). GPP was proposed to be function of Light Use Efficiency (LUE) multiplied by Absorbed Photosynthetically Active Radiation (APAR), where APAR = FPAR*IPAR (Incident Photosynthetically Active Radiation) can be retrieved from satellite measurements (Goetz et al., 1999). Hilker et al. (2008) recently discussed that inaccurate parameterization of LUE, which can be obtained only by indirect means, can introduce significant uncertainties in vegetation primary production estimates. Gamon et al. (1992) suggested that LUE of individual leaves could be empirically approximated via the photochemical reflectance index (PRI =

(R_{531}-R_{570})/(R_{531}+R_{570}), where R_{531} and R_{570} represent leaf reflectance at the subscripted wavelengths). However, PRI often failed to quantify photosynthetic efficiency in structurally heterogeneous canopies (Fillela et al., 2004). An alternative way to estimate LUE is measurement of chlorophyll fluorescence emissions. At room temperature, chlorophyll a emits fluorescence in the red and NIR (far-red) spectral region between 650-800 nm, in two spectral bands with peaks at λ_{max} ~ 684-695 nm and λ_{max} ~ 730-740 nm (Lichtenthaler and Rinderle, 1988). These red and far-red chlorophyll fluorescence (ChlF) emissions are highly temporally dynamic, being modulated by photochemical and non-photochemical quenching (Baker, 2008), which allows establishing a relationship to the actual photosynthetic LUE. Most widely used ground-based ChlF observations are active, using laser light source to excite the photosynthetic machinery. Lately, an eye safe outdoor laser induced fluorescence transient (LIFT) fluorometer has been constructed to measure the ChlF parameters from a distance of about 30-50 m (Kolber et al., 2005). However, airborne and future satellite fluorescence approaches are based mainly on solar-induced ChlF emissions inside and/or near to the solar Fraunhofer and atmospheric absorption lines. So-called Fraunhofer line discrimination (FLD) method has been applied to estimate ChlF in O_2-A (760 nm) atmospheric absorption line (Louis et al., 2005) from airborne data of the AIRFLEX a passive multi-wavelength fluorescence detector (Moya et al., 2004) and even MERIS satellite scenes. Because the intensity of the ChlF signals is low, relative to vegetation reflectance, the spectroradiometers of narrow bandwidth (c. 1 nm) and high signal-to-noise ratio are required for this type of observation. A new ESA (European Space Agency) airborne imaging spectrometer APEX (Airborne Prism EXperiment; Itten et al., 2008) will be operated by the Remote Sensing Laboratories (University of Zürich) since 2010. Concerning the space missions, the FLuorescence EXplorer (FLEX; Rascher et al., 2008) satellite will be proposed to ESA as one of the 8th Earth Explorer candidate missions in tandem with the GMES Sentinel-3 mission. Finally, a new generation of the multispectral LiDAR scanners is being proposed for a simultaneous three-dimensional remote sensing investigation of the vegetation canopy structure and photosynthetic performance (Morsdorf et al., 2009).

Key-words

Imaging Spectroscopy, Photosynthesis, Primary Productivity, NDVI, LAI, FPAR, LUE, Chlorophyll, Fluorescence, GPP, NPP.

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