ESTIMATION OF VEGETATION PHOTOCHEMICAL PROCESSES: AN APPLICATION OF THE PHOTOCHEMICAL REFLECTANCE INDEX AT THE SAN ROSSORE TEST SITE

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ABSTRACT

The Photochemical Reflectance Index (PRI) has been proposed as a tool for the estimation of leaf and canopy light-use efficiency and photosynthesis from remote-sensing data. The application of the index is based on more than fifteen years of spectroscopic studies at the leaf level, which support it with a sound physiological basis. In the present study, the correlation between PRI and instantaneous light-use efficiency was estimated across a range of vegetation types in the San Rossore Regional Park, a CHRIS-Proba core site. The relationship was also tested over an entire season for a pine forest in the Park where carbon fluxes have been monitored by eddy-covariance over the last five years. Seasonal changes in photosynthetic potential were also monitored at the site, in order to test the correlation with PRI reported in the literature. In September 2004, estimates of canopy PRI from CHRIS images were compared with leaf-level measurements from 13 plots corresponding to different vegetation types. The results were used to extrapolate leaf-level information to the entire scene.

INTRODUCTION

When exposed to an excess of irradiation, plants cannot use all the absorbed energy and as a photoprotective process increase both fluorescence and thermal energy dissipation without evident damage to the photosynthetic apparatus. Such a dissipation is the result of xanthophyll deepoxidation under conditions of low lumen pH, from violaxanthin via antheraxanthin to zeaxanthin (Demmig-Adams 1990). Even under unstressed conditions, however, the daily decline of photosynthesis efficiency can also be the result of photoinibition resulting in a reduction in maximum photosynthetic capacity. Moreover, plant growth environments may be limited by several stress factors such as nutrient, water, chilling or high temperature, which enhance the effect of high irradiation damages. Under prolonged high irradiance, damages to the photosynthetic apparatus may occur with some form of damage to the D1 protein, followed by pigment photo-oxidation and, at last, irreversible chlorophyll bleaching and leaf death (Choudhury and Behera, 2001).

The main function of xanthophyll cycle pigments (zeaxanthin, antheraxanthin and violaxanthin) in chloroplast is to increase non-radiative dissipation of excess irradiance as heat in the antenna of PSII and protect chloroplasts. The depoxidation of violaxanthin into zeaxanthin is driven by the acidification of chloroplast lumen and by this conversion the excess energy absorbed by PSII antenna is dissipated as heat. This photoprotection process, based in the antennas, is generally detected as ΔpH-dependent non-photochemical chlorophyll fluorescence quenching (NPQ, Demmig-Adams 1990), as the zeaxanthin binding with chlorophyll protein complex in the antenna of PSII also induces NPQ of chlorophyll fluorescence as well as electron transport and provides protection against high irradiance. The possibility of detecting the zeaxanthin content by foliar reflectance by the reflectance at 531 nm normalized to the 570 nm reference was proposed by Gamon et al. (1990) and synthetized in the photochemical reflectance index (PRI), and could open the way to determine directly light use efficiency by remote sensing. The CHRIS-Proba platform offers a unique opportunity to validate this hypothesis under several environmental conditions. In particular, this study was aimed at determining (i) the relationship of PRI and NPQ for several vegetation types under high irradiance under mediterranean summer midday conditions, (ii) the relationship between PRI measured on the ground and retrieved from CHRIS-Proba images.

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MATERIALS AND METHODS

Sampling areas during CHRIS-Proba 2004 campaign
In the Natural Park of San Rossore (43°43'N, 10°20'E; Pisa, Italy), 13 ground areas covering different vegetation types (including crops, herbs, shrubs, deciduos broadleaves, evergreen sclerophylls and conifers) were sampled on 8th September 2004 on the same day of the CHRIS-Proba overpass (Table 1, Fig. 1).

Table 1 List of ecosystems sampled for midday reflectance on the 8th September 2004, type, number (n) and dominant species; between parenthesis the number of sites sampled for each vegetation type.

vegetation type	n	dominant plant species
crops, herbs and shrubs	4	*Medicago sativa* (1), *Phragmites australis* (1), *Rubus fruticosus* (1), *Silybum marianum* (1)
deciduos broadleaves	4	*Populus* x *euroamericana* (1), *Fraxinus angustifolia* (2), *Alnus glutinosa* (1)
evergreen sclerophylls	1	*Quercus ilex* (1)
conifers	4	*Pinus pinaster* (1), *Pinus pinea* (3)

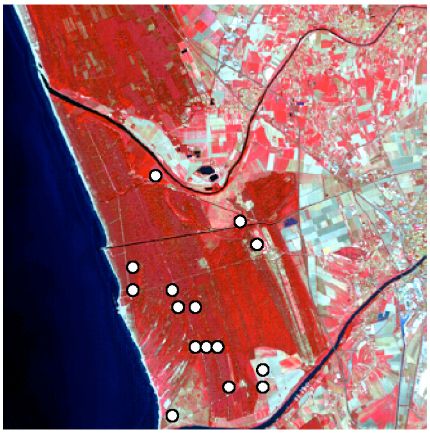

Fig. 1. Ground sampling areas position within the CHRIS core site of the Natural Park of San Rossore (43°43'N, 10°20'E; Pisa, Italy) on the imagery collected in mode 3 with MZA=-9, FZA=0, on the 8th September 2004 and corrected for radiometric, geometric and atmospheric effects by CNR/IFAC (Florence, Italy). The RGB channels of the image are 873.6 nm, 698.3 nm, 551.8 nm, resp., (corresponding to channels 14, 8, 4 of mode 3 CHRIS). The white circles refer to ground localization of sampling areas.

Measurements during the field campaigns
Ground measurements were carried out in the field at midday between 10:30 and 14:30 pm on the same day of the CHRIS overpass. The upper part of the crown was sampled by taking reflectance and fluorescence measurements on representative samples of 15-30 leaves selected from several plants. In the case of forest canopies an articulated boom mounted on a truck was used. Leaf reflectance of the adaxial part of the leaf was measured with an USB-2000 spectrometer (Ocean Optics, Florida, USA) with 0.4 nm of sampling interval and a FWHM of 1.3 nm connected with a bifurcated low-OH optic fiber with a central fiber of measurement surrounded by 8 fibers of illumination connected with a stabilized light source (LS-1 Ocean Optics) and held at an angle of 45° on the darkened leaf. Reflectance spectra and their first derivative were smoothed by a Savitsky-Golay filter with a window of about 20 nm and order 3 before calculating reflectance indices and red edge position, respectively.

Reflectance indices where calculated as follows:

Photochemical Reflectance Index (Gamon *et al.* 1990),

$$PRI = \frac{(R_{531} - R_{570})}{(R_{531} + R_{570})},$$

Normalized Difference Vegetation Index,

$$NDVI = \frac{(R_{782} - R_{675})}{(R_{782} + R_{675})},$$

where R is reflectance at a given wavelength in nm indicated by the suffix.

Chlorophyll fluorescence emission was measured with a PAM-2000 modulated chlorophyll fluorometer (Walz, Effeltrich, Germany) maintaining the leaf in its natural position. The leaf clip holds the PAM fiber optic at angle of 30° on the leaf plane. The leaf temperatures and photon flux densities incident upon the leaves were measured using the sensor integrated into the leaf clip. After measurements leaves were collected, placed in wet and dark conditions at 20°C for 24 h and then re-measured in order to have dark-adapted values for reflectance and fluorescence. Quantum yield of photosystem PSII was estimated by ΔF/F'm, maximum quantum yield by Fv/Fm, electronic transport rate as ETR=0.5*0.8*PAR*ΔF/F'm, and non photochemical quenching as NPQ= (F°m-F'm)/(F'm), (see Maxwell and Johnson, 2000 for details). Leaves were then scanned and dried for 48 h at 80°C in order to calculate leaf mass per area (LMA).

CHRIS image analysis

A CHRIS image acquired on on 8th September 2004 was used for the assessment of PRI at the San Rossore site. The nadir, -36° and +36° images were used in this preliminary analysis. Images were collected in mode 3 with MZA = -9°, and corrected for radiometric, geometric and atmospheric effects by CNR/IFAC (Florence, Italy) as described elsewhere in this volume.

PRI and NDVI were finally estimated from CHRIS images, based on measured reflectance at 530.5, 570.5, 675.4 and 782.1 nm.

RESULTS AND DISCUSSION

The good correlation of PRI and leaf non-photochemical quenching (NPQ, a measure of excess energy dissipation), as well as light-use efficiency (estimated from modulated fluorescence as $\Delta F/F'_m$), has been confirmed across a large number of species and in response to a wide range of stress conditions. In Fig. 2 the relationship was reported for the data acquired during the CHRIS field campaigns in May and in September, and in the laboratory after acclimatation to saturating light conditions (PAR>1500 μmol m^{-2} s^{-1}).

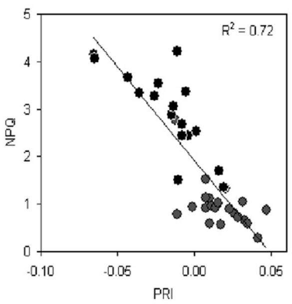

Fig. 2. Relationship between non photochemical quenching (NPQ) and photochemical reflecance index (PRI) for the data collected on the field during the CHRIS-Proba campaigns in May and September (black circles) on the sampling sites at midday reported in Figure 1 and in the laboratory in saturating light conditions (gray circles)

The correlation between PRI and $\Delta F/F'_m$ is the result of the functional link of both parameters with leaf non-photochemical quenching (NPQ). Under extreme drought conditions, $\Delta F/F'_m$ is known to decline even in the absence of any NPQ, because of long-lasting photoinhibition. The dark relaxed leaves had quantum yield (Fv/Fm) values ranging from 0.69 to 0.83, with the exception of helm oak, which showed a chronic photodamage (with Fv/Fm of 0.49). The other vegetation types did not suffer from photodamage and showed an average value of 0.79, not far from 0.82, the theoretical maximum value of the index (Demmig-Adams and Adams, 2000).

Based on measurements at the leaf level, the comparison between PRI calculated with the spectrometer bands nearest to the wavelengths at 531 nm and 570 nm reported in the literature for the index and the PRI calculated with the signal degraded to CHRIS band specifications showed an almost perfect 1:1 relationship, indicating the suitability of CHRIS mode 3 to monitor PRI (Fig. 3), despite the different spectral resolution (8.6 vs 0.3 nm).

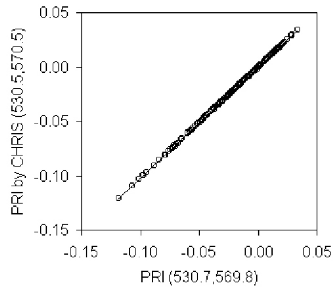

Fig. 3. Relationship between photochemical reflectance index (PRI) on leaves measured with a field spectrometer and the equivalent index calculated degrading the signal to CHRIS channels 3 and 5 in mode 3 corresponding to 531 nm and 570 nm

The preliminary analysis of one CHRIS image (8th September 2004, nadir view, MZA ~ -12 deg) demonstrates the feasibility of PRI measurement from space. A good relationship was observed between PRI measured at the leaf level as ground truth and PRI calculated from CHRIS imagery (R^2=0.45). The correlation improves (R^2=0.57) when the helm oak stand is excluded (because characterized by chronic photodamage and high pubescence of the abaxial part of the leaves, Fig.4). In the latter case the PRI_{ground} vs PRI_{CHRIS} is maintained also for the other two images at +36° and –36° of FZA we have analysed with R^2 of 0.69 and 0.41, respectively.

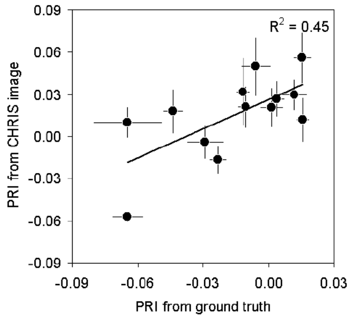

Fig. 4. Relationship between PRI measured in the field the 8th September 2004 on the 13 sampling areas of Tab 1 and PRI retrieved from CHRIS imagery. In the graf averages and standard deviations were reported for each area

Despite the noise of such a small signal, values are coherent across the image and differences among and within vegetation types are clearly visible, as apparent from a comparison of PRI and NDVI gray scale images in Fig. 5 and 6, respectively.

The correlation with NDVI for the ground truth points selected is apparent from Fig. 7. Leaf area index (and hence NDVI) is known to be generally correlated with fertility and light-use efficiency, and this could explain the relationship with PRI. However, in the relationship between PRI and NDVI a considerable scatter was observed even in the nadir view, making PRI not redundant. Moreover the relationship of PRI and NDVI highlighted in CHRIS imagery appears to be mainly driven by reflectance in the red channel at 675 nm, while reflectance in the near-infrared is not related to PRI (Fig. 7). This may suggest an effect of soil reflectance in the observed relationship. And as a matter of fact, at leaf level, no correlation was observed between PRI and NDVI (R^2=0.11^{ns}, Fig. 8).

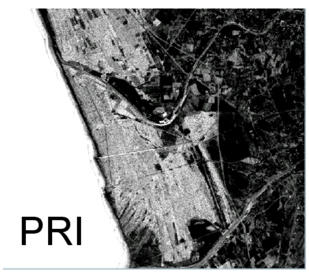

Fig. 5 Fig. 6

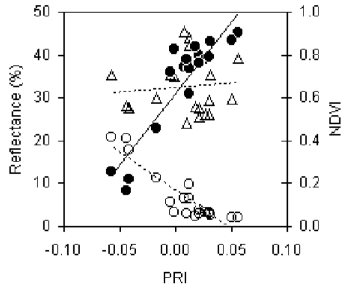

Fig. 7

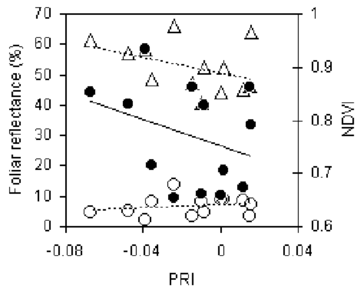

Fig. 8

Figs. 5-8. Reflectance normalized indices imageries relative to PRI (with bands 3 an 5 of CHRIS mode 3 corresponding to 530.5 and 570.5 nm, resp., Fig.5) and NDVI (with bands 14 an 8 of CHRIS mode 3 corresponding to 782.1 and 675.4 nm, resp., Fig. 6) for the 8th September 2004 CHRIS acquisition with MZA=-9 and FZA=0. On land, dark values of PRI and NDVI correspond to almost bare agricultural land, white values to high values of PRI and NDVI, as highlighted by the strong positive relationship between the two indices reported in Fig. 7 for the 13 ground sampling areas (R^2=0.88**). On the contrary at leaf level PRI and NDVI, calculated with the same CHRIS wavelengths as the previous figures, were not correlated (R^2=0.11ns), Fig. 8. Open trangles and open circles in Figs 7 and 8 referred to reflectance at 782.1 nm and 675.4 nm, resp.

Moreover, if CHRIS-based reflectance spectra were corrected for a linear effect of soil the effect of soil reflectance is confirmed by the analysis of CHRIS, no relationship could be observed between PRI and NDVI (R^2=0.21^{ns}, data not shown). The effect of soil reflectance is confirmed by the analysis of CHRIS imagery at +36° and –36° where, once excluded the strong leverage effect of agricultural areas with a low cover fraction of green vegetation, the R^2 of the relationship is no more significant (R^2 < 0.30 for NDVI>0.6).

CONCLUSIONS

Remote sensing studies have so far focused on the determination of light absorption, but photosynthetic light-use efficiency cannot be assumed to be constant.

The Photochemical Reflectance Index (PRI) has been proposed for the estimation of light-use efficiency. the index is based on a strong body of experimental studies at the leaf level.

The good correlation between PRI and leaf non-photochemical quenching (NPQ, a measure of excess energy dissipation), as well as light-use efficiency (estimated from modulated fluorescence as $\Delta F/F'_m$), has been confirmed in the present study across species and in response to a wide range of stress conditions (drought, cold stress), in the absence of extreme stress and photodamage (which is unusual under field conditions).

CHRIS appears particularly suitable for the determination of vegetation PRI from space, because of spectral characteristics and viewing geometry.

A preliminary analysis has demonstrated the feasibiliy of PRI measurements from space. Although small, the signal is coherent and (partly) correlated to other vegetation indexes. However, the PRI signal appears to be strongly affected by soil reflectance, so requiring for a succefull analysis either correction or the use of tilted images.

Future work will include:

- Analysis of multi-temporal series of CHRIS images (nadir view, hemispherical reflectance in collaboration with CTCD) for 2003-4, correlation with ground measurements at the leaf (photosynthesis, reflectance) and canopy level (GPP from eddy-covariance);
- 3-year extension of ground truth measurements at the San Rossore site through the Carbo-Italy project;
- Development of automated spectrometer for continuous VIS-NIR measurements from above the canopy;
- Request for 12 CHRIS images over 2005 (mode 3);
- Analysis of eddy-covariance data through inversion of HYDRALL ecosystem model, estimation of light-use efficiency and photosynthetic potentials, correlation with PRI.

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