ANGULAR CHLOROPHYLL INDICES ESTIMATES DERIVED FROM GROUND-BASED DIURNAL COURSE DATA AND MULTIANGULAR CHRIS-PROBA DATA: TWO CASE STUDIES

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ABSTRACT

At leaf and plant level chlorophyll indices have shown strong correlations with chlorophyll content and photosynthesis-related processes. However, at canopy level additional abiotic and biotic factors confound the fidelity of these indices. For instance, the Photochemical Reflectance Index (PRI) is known to be sensitive to viewing angles and canopy structure. In this paper we present case studies of two natural canopies at different scales where the influence of sun-target-sensor geometry and canopy structure is inter-compared for a range of chlorophyll indices.

In the first case study, surface reflectance was measured in a montane grassland ecosystem located at the Bily Kriz experimental study site (Czech republic) using a stationary mounted AISA (Airborne Imaging Spectrometer for Applications) spectrometer. The experimental set-up resulted in a ground pixel resolution of ~2mm. The effects of changing sun angles on the indices were assessed through a diurnal sampling between 9:00 and 15:00 hrs (local time). Classes of shaded and illuminated photosynthetic (PV) and non-photosynthetic vegetation (NPV) were distinguished per image using a pixel wise classification. The relative contributions of confounding factors as well as the influence of the diurnal variability on performance of the selected chlorophyll indices were evaluated.

In the second case study, surface reflectance was measured over an Alpine coniferous ecosystem in the Swiss National Park (Switzerland) using multiangular hyperspectral CHRIS-PROBA (Compact High Resolution Imaging Spectrometer onboard the Project for On-board Autonomy) satellite system with a ground pixel resolution of 17 m. The angular signature of PRI and the structure invariant pigment index (SIPI) was assessed using CHRIS data. Besides, we evaluated the influence of varying tree crown composition and varying viewing angles to the chlorophyll indices with a radiative transfer model FLIGHT.

In both cases, the PRI and the green NDVI (gNDVI) responded extremely sensitively to the considered confounding factors at canopy level. The Transformed Chlorophyll Absorption in Reflectance Index normalized by the Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI), designed to be insensitive to background and LAI variations, responded more sensitively than the conventional NDVI. No certain sensitivity was found for SIPI. The pronounced sensitivity of e.g. PRI and gNDVI, on one hand, and the inconsistency between the chlorophyll indices, on the other hand, erodes the fidelity to use these spectral indices as an effective non-destructive chlorophyll detector.

INTRODUCTION

With the advent of hyperspectral imaging, numerous optical vegetation indices (VIs) have been proposed in the literature to retrieve chlorophyll content from spectroradiometric data. The main aim of these chlorophyll-sensitive indices - or simply chlorophyll indices - is to identify optimal mathematical formulations of spectral bands in order to maximize the sensitivity to chlorophyll content, while minimizing variations arising from other confounding factors. Within this family of indices, the Photochemical Reflectance Index (PRI) (1) has taken the advantage of existing specific spectral feature sensitive to dynamic photosynthetical processes. At leaf and plant level, this index has shown good correlations with short-term and diurnal changes in zeaxanthin pigment concentration (1,2) and fluorescence parameters, that are related to zeaxanthin (3), and thus to light use efficiency (LUE) parameter (4). PRI also tracks seasonal changes in leaf-level photosynthetic capacity (6) but tends to be species specific (7). However, PRI is affected not only by xanthophyll cycle activity, but also indirectly by other abiotic and biotic factors. At leaf level external factors are generally well controlled, but once up-scaling to canopy level, additional factors notably affect the relationships. Examples of airborne (8, 9, 10), satellite-based (11, 12) studies and a modelling study (13) reported that PRI measures are substantially distorted by the fraction of non-photosynthetic vegetation (NPV; woody elements, e.g. branches, trunks) and the fraction of soil present in a pixel (14, 15).

The problem for chlorophyll indices when up-scaled to canopy level is the propagation of increased complexity due to canopy composition and bidirectional reflectance distribution function (BRDF) effects. In its simplest form, a natural canopy can be considered as a unique and complex volumetric composition of photosynthetic vegetation (PV) elements and NPV elements and possibly soil elements, which each of them are either in sunlit or shaded state. The observed proportions of these elements depend on the sun-target-sensor geometry, and each of these elements affects the reflectance signal. Furthermore, only from the detected PV elements chlorophyll content or photosynthesis-related information can be retrieved, whereas all the other elements play role of distorters.

Apart from PRI, also other chlorophyll indices gained popularity in ecophysiological studies at canopy level. Some of these indices were specifically developed to stay invariant to influence of these confounding factors, such as the Structure-Invariant Pigment Index (SIPI) (16) or the Transformed Chlorophyll Absorption in Reflectance Index normalized by the Optimized Soil-Adjusted Vegetation Index (TCARI/OSAVI) (17), designed to be insensitive to background and LAI variations). However, the robustness of the indices to canopy composition and BRDF effects is largely unknown and hence seriously erodes the reliability of the retrieved products. Therefore, prior to consider the use of chlorophyll indices at canopy level as an effective non-destructive chlorophyll detection method, the following key question ought to be clarified:

Is there sufficient fidelity that the estimates of chlorophyll-related indices can be truly interpreted with respect to chlorophyll content or photosynthesis-related processes?

To answer this question, we present case studies of two natural canopies where we quantify in either case the response of chlorophyll indices to varying sun-target-sensor geometry and canopy composition. This implies that the scope of this work was not to evaluate how well a chlorophyll index was correlated with field-measured chlorophyll estimates, but rather how sensitively an index responded to one of the aforementioned confounding factors. As a result of this analysis we categorized the indices in terms of its robustness to the tested distorters. The case studies are:

- *Diurnal ground-level AISA data of a Montane grassland (Bily Kriz, Czech republic)*

  With an AISA sensor mounted downwards a tripod at 4m height, diurnal hyperspectral data of a super spatial resolution of ~2mm over a heterogeneous meadow was acquired. The high spatial resolution enabled the discrimination of single canopy components. While a range of diurnal data acquisitions enabled the assessment of the effects of changing solar angle.

- *Angular CHRIS data of a Coniferous forest (Swiss National Park, Switzerland)*

  Spaceborne multiangular CHRIS data acquired above a heterogeneous old-growth forest provided unprecedented capabilities to assess the angular variability of narrowband indices. By using a 3D radiative transfer model called FLIGHT (25) we compared CHRIS-derived angular VI signatures with simulated VI signatures. With FLIGHT we systematically evaluated how chlorophyll indices respond to changing viewing angles and changing canopy composition.

METHODS

Both case studies focus on the response of several chlorophyll indices as a function of sun-target-sensor and canopy composition variability. But they differ in scale and approach. The meadow study uses ground-level super-resolution AISA data to assess the effects of diurnal change on canopy composition, whereas the forest canopy case study uses CHRIS data and FLIGHT to assess the effects of variable viewing angles and canopy structure.

The selected chlorophyll indices are presented in table 1. Since the behaviour of the NDVI is already well understood, the index is added as a reference index. The chlorophyll indices are: PRI, SIPI, gNDVI (green NDVI) and TCARI/OSAVI.

Table 1. Selected VIs used in this study with a central wavelength corresponding to both, AISA and CHRIS-PROBA bands.

Index	Algorithm	Measure of
NDVI (18)	$\frac{(R_{780}-R_{672})}{(R_{780}+R_{672})}$	greenness
PRI (1)	$\frac{(R_{530}-R_{570})}{(R_{530}+R_{570})}$	Light use efficiency
SIPI (16)	$\frac{(R_{780}-R_{443})}{(R_{780}+R_{705})}$	Carotenoid and Chl a Insensitive to structure
TCARI/OSAVI (17)	$\frac{3*[(R_{700}-R_{672})-0.2*(R_{700}-R_{562})*(R_{700}/R_{672})]}{(1+0.16)*(R_{800}-R_{672})/(R_{800}+R_{672}+0.16)}$	Chlorophyll content Insensitive to LAI and background variations
gNDVI (19)	$\frac{(R_{555}-R_{677})}{(R_{555}+R_{677})}$	Chlorophyll

Further, the eventual influence of the dissimilar AISA and CHRIS bandwidths on the VI results were evaluated with AISA data by means of a linear regression. The high correlations for each index (R2>0.99) provided confidence that the different bandwidth configuration of AISA sensor (2 nm FWHM) and CHRIS (10 nm FWHM) had a negligible effect on the computed VIs values.

In either case study, each index was normalized variance as follows:

$$\Delta\mathrm{VI} = \frac{VI_{variable} - VI_{reference}}{VI_{reference}} * 100\% \qquad (1)$$

where the reference corresponds to solar noon (12:30u) and nadir values in the case of AISA and CHRIS respectively.

Case study I: Sensitivity of montane grassland vegetation indices using diurnal AISA data measured at ground

Data acquisition and study site

In the first case study we evaluated the effects of diurnal changes on the indices using ground-based nadir measurements. At 4 m above a meadow canopy an hyperspectral AISA Eagle was mounted downwards a tripod. Fife measurements were consecutively taken from 9:00 local time until 15:00 (Table 2). A montane grassland research plot, located at the Bily Kriz experimental study site (18.54°E/49.49°N, 898 m a.s.l.) in the Beskydy Mts. (Czech republic), was chosen as test site due to its high species diversity, with around 25 herbaceous species (phytocenological analysis in 2004). The most abundant species at the measured plot were *Festuca rubra agg.*, *Hieracium sp.*, *Plantago sp.*, *Nardus stricta* and *Jacea pseudophrygia*. The Beskydy Mts. are characterized as cool and humid with annual precipitation of about 1000 – 1400 mm. The Leaf Area Index (LAI) of the grass canopy was during the data acquisition between 3 and 3.5. The inclination of the plot was slight, with orientation to south-east.

Table 2. AISA sensor configuration during diurnal measurement.

Sampling	Image area	Sun zenith angles	Local time	Spectral bands	Spectral range
~2.2 mm @ 4 m altitude	1 x 3 m (500 x 1500 pixels)	5 nominal angles @ - 51°, 35°, 26°, 29° and 38°	5 nominal times @ 9:00, 11:00, 12:30, 14:00 and 15:00	260 bands with 2nm width	450-940 nm

Classification and resampling

In order to identify the diurnal variability occurring at ~2mm scale, the fife meadow images were classified using the Maximum Likelihood classifier into four classes: i) fully sun-exposed green vegetation, ii) partly shaded vegetation (S: green leaves under diffuse light), iii) vegetation under “deep shade” (DS: dark parts deeply penetrated in the canopy), and iv) non-photosynthetic vegetation (NPV: flowers, dry leaves) (Figure 1). The influence of the confounding classes NPV and shade (S and DS) on the indices will be further analyzed. Next, the original spatial resolution was resampled to a much coarser resolution (0.1x0.2m). With this classified image not only the effects of NPV and shade on the indices can be assessed, but also the effects of the diurnal course per canopy class.

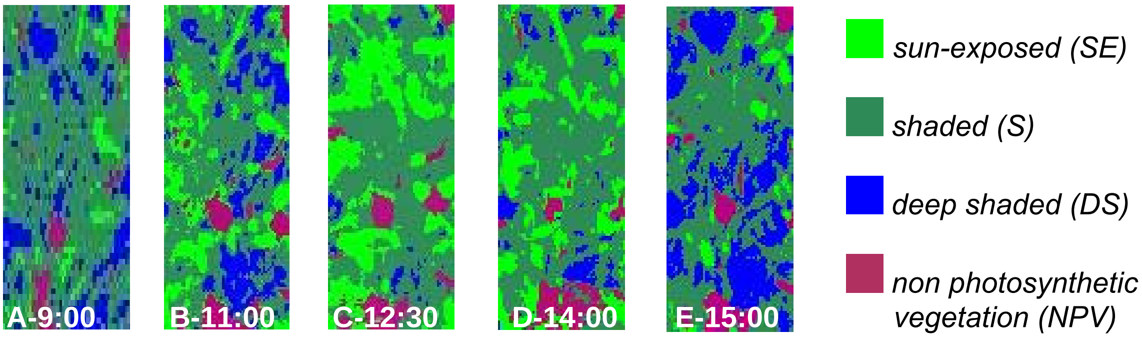

Figure 1: Automatic classification of the representative area in diurnal course (pixel size of 0.1x0.2m; N=8145 pixels). The overall classification accuracy was between 83.1-87.8% with kappa coefficient between 0.78 – 0.83.

For each index, the influence of each single confounding class (CC: S, DS or NPV) was evaluated by plotting per resampled pixel the relative influence against the fraction of that confounding class. The relative VI influence is compared to the VI value of the joined fractions of SE and CC:

$$VI_{\text{Relative difference}} = VI_{.(SE + CC)\text{ fraction}} - VI_{CC\text{ fraction}} \qquad (2)$$

where $VI_{SE\text{ fraction}}$ is the index value of the sun-exposed (SE) pixels and $VI_{CC\text{ fraction}}$ is the index value of a given confounding class.

From each of these plots a linear regression was drawn and significance of the slope was tested. Subsequently, the steepness of the slope indicates the dependency on a given class. Finally, for each index the normalized diurnal course (Eq. 1) was determined, both for the mixed pixels as well for the sunlit-exposed class.

RESULTS

Regarding the nadir-detected diurnal variability of the meadow classes, most of the observed changes were due to changes in sun-exposed vegetation (4-32%) trading off with vegetation under deep shade (4-25%) as a result of changing solar angles (Figure 2). The fraction of NPV (between 5-7%) and shaded vegetation (between 58-66%) stayed relatively constant during the daily course. The observed high fraction of green vegetation under diffuse light (S pixels) is likely due to the grass structure dominated by erectophyl plant types.

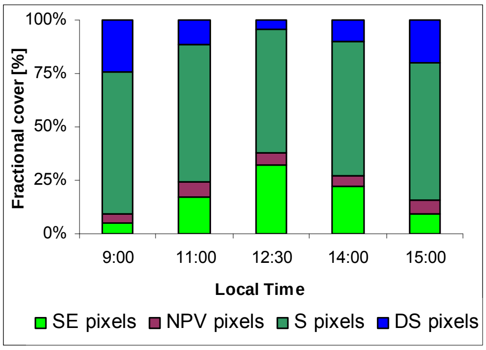

Figure 2: Histogram showing diurnal variation in defined classes.

The contribution of the distorters (i.e., S, DS, and NPV) was assessed for each index by evaluating the slopes of the linear regressions (Figure 3). A negative slope indicates a decrease of the index values at canopy level due to a given class (see performance of NPV). In case of TCARI/OSAVI even all distorters had a negative impact on the signal. A positive slope means that a given class is responsible for an increase in the index response at canopy level (in most cases of S and DS).

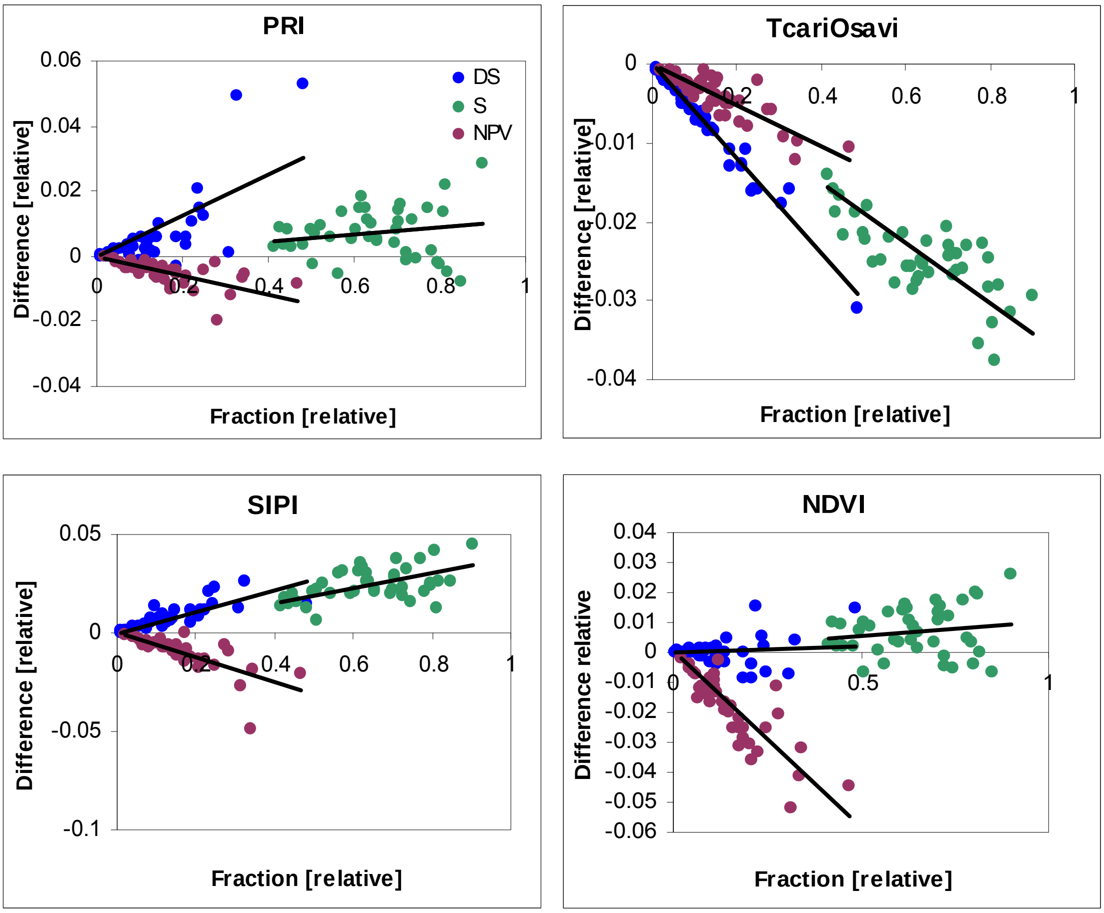

Figure 3. Sensitivity of PRI (A), TCARI/OSAVI (B), SIPI (C) and NDVI (D) to deep shade (DS, blue), shade (S, green) and non-photosynthetic vegetation (NPV, red) at 12:30 (local time).

When comparing the slopes of all diurnal data (Table 3), the gNDVI index responded strongly to the confounding factors, with oscillating negative and positive slopes during the day for the S and DS fractions. The slopes of the other indices were more consistent during the day period. PRI and TCARI/OSAVI were sensitive to DS fraction, while NDVI and SIPI were less affected by the considered distorters. In general, each VI showed higher sensitivity to DS than to S fraction. Hence, we recommend being careful when interpreting chlorophyll indices results for canopies with significant fraction of deep shade.

Table 3. Slopes of linear regressions of compared VIs in the diurnal course. Asterisks show statistical significance of linear regression at p<0.05(*) and p< 0.01(**) levels.

Time	**distorter**	**PRI**	**TCARI/OSAVI**	**NDVI**	**gNDVI**	**SIPI**
9:00	*DS*	0.135**	-0.126**	0.086**	0.193*	0.035*
	S	0.034*	-0.078**	0.051	0.009	0.016
	NPV	-0.003	-0.070**	-0.06**	-0.352**	-0.123**
12:30	*DS*	0.062	-0.060**	0.022	-0.231**	0.054**
	S	0.010	-0.037**	0.033	-0.078**	0.037**
	NPV	-0.030**	-0.027**	-0.117**	-0.382**	-0.060**
15:00	*DS*	0.096**	-0.092**	0.069**	0.010	0.025*
	S	0.027**	-0.058**	0.048*	0.037	-0.006
	NPV	-0.011	-0.052**	-0.088**	-0.358**	-0.142**

The stronger sensitivity of PRI and gNDVI can be explained by wavelengths of only visible part used for their computation. Low vegetation reflectance in the visible wavelengths can cause big differences between two adjacent bands when normalized. However, a similar sensitivity of TCARI/OSAVI, which also uses a NIR wavelength, was in this context unexpected, because TCARI/OSAVI was designed to be a robust index for LAI and background variability.

Diurnal course

When observing the sun angle effects for all pixels (Figure 4A) then each VI showed an increasing trend with increasing SZA, except for TCARI/OSAVI. The reason for this increase is higher fraction of shaded vegetation. Similar observations were found at canopy level for NDVI (17, 18). The fluctuating behaviour of TCARI/OSAVI can be partly explained by the negative sensitivity to shade. PRI has a remarkable higher variability that can be potentially explained by the high sensitivity to the deep shade vegetation (Table 3). Also, because at noon the PRI value was close to zero (normalization value: 0.015), a similar change as for instance for the NDVI (normalization value: 0.9), will result in a much higher variability.

The NDVI, SIPI and gNDVI values showed a slight decrease with decreasing SZAs when isolating only green sun-exposed pixels (Figure 4B). Conversely, PRI showed again a pronounced angular response, closely followed by TCARI/OSAVI. Whether this variability can be related to the varying diurnal concentration of the zeaxanthin pigment remains questionable. In fact, diurnal chlorophyll measurements on the same grassland plot one year earlier (2005) did not exhibit any significant diurnal course.

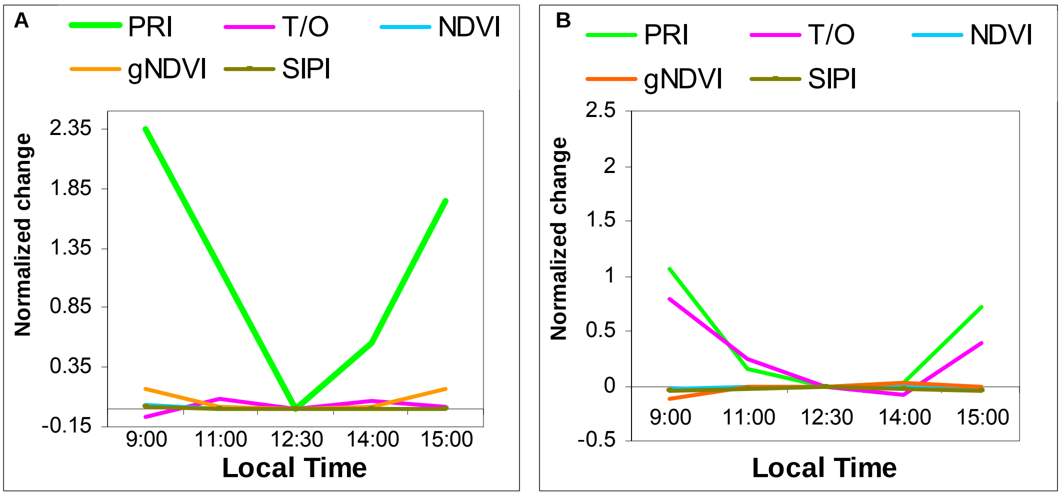

Figure 4. Noon-normalized diurnal courses of VIs for all pixels (A) and for sun-exposed pixels only (B).

Finally, from each angular signature the standard deviation (SD) of normalized VI's values was calculated as a quantitative measure of their inter-comparability (Table 4). Considering all pixels as well as solely sunlit pixels the PRI outreached the other indices. The SD works properly as long as the index does not fluctuate around the normalized value, as is the case for the TCARI/OSAVI of all pixels. TCARI/OSAVI and gNDVI showed considerable variability while NDVI and SIPI stayed rather invariant.

Table 4. Normalized standard deviations as calculated from values in figure 4.

Normalized SDs	**PRI**	**TCARI/OSAVI**	**NDVI**	**gNDVI**	**SIPI**
All pixels	9.32	0.54	0.11	0.85	0.08
Sulit pixels	4.77	3.5	0.1	0.57	0.2

Case study II: Sensitivity of coniferous forest vegetation indices using multiangular CHRIS-PROBA data and FLIGHT modelling

Data and study site

This second case study capitalizes on the use of a unique combination of hyperspectral and directional data set provided by CHRIS-PROBA. The CHRIS data set ideally has the capabilities to assess the angular response of various narrowband vegetation indices. Its specifications are shown in table 5. The used CHRIS image set, acquired on June 27 2004 10:41h AM local time under partly cloudy conditions (1/8th cloud cover), was geometrically and radiometrically corrected following an approach dedicated for rugged terrains (22). Five scenes of the test site had a geometric accuracy of 1-2 pixels. The generated 'surface reflectance' represents hemispherical-directional reflectance factor (HDRF) (23). The +21° scene is the (near-) nadir scene while the -55° scene happened to be viewing predominantly back scattering (Figure 5).

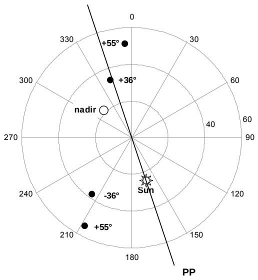

Table 5. CHRIS configurations for Land Mode 3

Sampling	Image area	Spectral bands	Spectral range
~17 m @ 556 km altitude	13 x 13 km (744 x 748 pixels)	18 bands with 6-33nm width	447-1035 nm

Figure 5. Polar plot of CHRIS acquisition and illumination geometry as of June 27, 2004. PP: principal plane

The study site is located in the eastern Ofenpass valley, which is part of the Swiss National Park (SNP) in South East Switzerland (10°13′48″E/46°39′45″N). The Ofenpass represents a dry inner-alpine valley with rather limited precipitation (900-1100 mm/a) on an average altitude of about 1900 m a.s.l.. The south-facing slope of the Ofenpass valley is considered as the core test site. The evergreen coniferous forest is dominated by mountain pine (*Pinus Montana ssp. arborea*). The forest structure is characterized by varying density and a relatively high fraction of woody elements (ca. 30%) due to the advanced age of the pine forest and nature management practice that stopped 70 years ago. Average LAI is 2.2 (1.0 SD). The understory is characterized by low and dense vegetation composed mainly of *Vaccinium, Ericaceae*, and *Seslaraia* species.

In a previous work using CHRIS data of the SNP coniferous forest (24) several vegetation indices gave sign of a pronounced anisotropic behaviour, particularly indices related to chlorophyll and other foliar pigment. It was suggested that an eventual increased proportion of NPV could significantly affect those chlorophyll VIs. In this study it was assessed whether the above suggested hypothesis is valid by using a radiative transfer model FLIGHT (25), where viewing angles and canopy composition can be systematically controlled.

FLIGHT modelling

With FLIGHT, evaluation of the Bidirection Reflectance Factor (BRF) is achieved by deterministic photon ray tracing within the discontinuous environment of a simulated forest canopy. The model allows the representation of complex vegetation structures and a correct treatment of spectral mixing resulting from multiple scattering within the scene. FLIGHT simulates a 3D forest canopy by geometric primitives with defined shapes and positions of individual stands with associated shadow effects. Within each crown envelope foliage is approximated by volume-averaged parameters with optical properties of both leaf (PV) and woody scattering elements (NPV) (25).

We simulated canopy reflectance consisting of stands with crown envelopes of various PV-NPV mixtures as a function of field-measured canopy variables and CHRIS acquisition geometries. The distribution of PV and NPV elements within the crown was random. We firstly modelled canopy reflectance for stands with solely NPV elements, followed by stands consisting of PV-NPV mixtures with consecutive PV increments of 20%, up to finally stands with solely PV elements. As for FLIGHT parameterization the averaged field measurements of four core test sites within the forest were used (table 6). The foliage optical properties were modelled by PROSPECT (26) coupled with FLIGHT (27) while the spectral properties of the woody parts and understory were characterized by spectrometric field measurements. The spectral properties of the vegetated understory were kept constant. This implies that even for a 100% NPV stand, due to the relatively low LAI and fractional cover, the signal still behaved as a typical vegetation signature.

Name	Value/ Range	PV	NPV
Fractional cover (%)	0.64		
Leaf Area Index	2.4		
Fraction of green foliage (%)		100%	0%
Fraction of bark (%)		0%	100%
Incident zenith (°), θ_i	24.0		
Reflected zenith (°), θ_r	-54.6, -37.8, +21.2 (nadir), +33.3, +51.1		

Table 6. Averaged input variables for FLIGHT parameterization collected at four test sites. (Remaining input variables are described in (26))

Once having the simulations completed, indices can be calculated as a function of PV-NPV mixture and viewing angle. By increasing the NPV fraction at greater zenith angles the assumption of a likely greater contribution to an angular VI signature can be assessed.

Further, a sensitivity study was conducted by calculating per-index the variance of varying canopy composition and viewing angle combinations. This was done as follows. First, for each PV-NPV combination the normalized angular change was compared to a reference angle (nadir) according to equation (1).

Next, from the generated ΔVI's for each viewing angle the variance (σ^2) of the PV-NPV mixtures was calculated. Since each index is normalized to a standard reference point the variance could be interpreted as a standardized measure of canopy structure spread in comparison to viewing angles. As such, quantitative comparison between the indices was possible. Finally, the above procedure was repeated but then by normalizing each PV-NPV combination to a reference of 60-40% of PV-NPV and then calculating the variance of the viewing angles.

RESULTS

The hypothesis that a greater contribution of NPV at greater viewing angles affects the angular signature of chlorophyll indices was tested for PRI and SIPI in figure 6. The upper left figure shows the angular PRI signature normalized against the nadir value as measured by CHRIS for the study site. The upper right figure shows normalized FLIGHT-modelled PRI's derived from various PV-NPV combinations. The values were normalized against a reference of 80%PV at nadir position. The FLIGHT results clearly show that when increasing the NPV content at greater zenith angles, the PRI response tend to fall down, virtually reaching a shape as observed by CHRIS. With SIPI, however, rather invariant responses were observed, both by CHRIS, both by FLIGHT with changing NPV fractions.

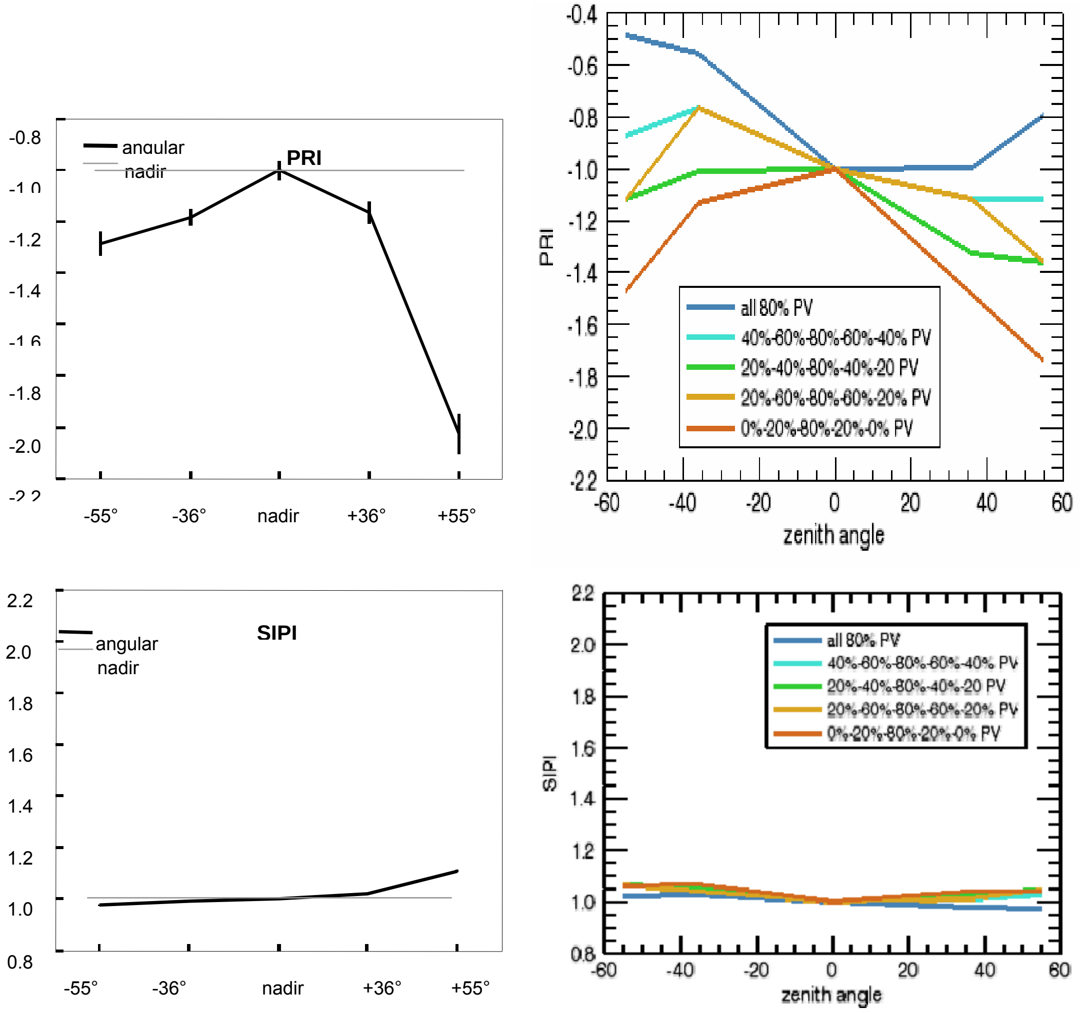

Figure 6. Averaged angular PRI and SIPI from forest acquired by CHRIS with error bars of ± 1 SEM (a). PRI derived from FLIGHT-BRFs with varying fractions of PV and NPV along the CHRIS viewing geometry (b). (%NPV= 100-%PV)

Chlorophyll indices sensitivity analysis

The sensitivity analysis consisted of two parts: (1) normalizing the indices that are calculated for all combinations (viewing angle – canopy composition) to a standard value, and (2) calculating the variability of these normalized indices by means of the standard deviation (SD=$\sqrt{\sigma^2}$). The results of first part of the sensitivity assessment are shown in Figure 7 where for each PV-NPV combination the angular response was normalized to nadir position. These graphs clearly show that PRI and TCARI/OSAVI responded strongly anisotropic when increasing the PV fractions, while SIPI and NDVI responded rather invariant.

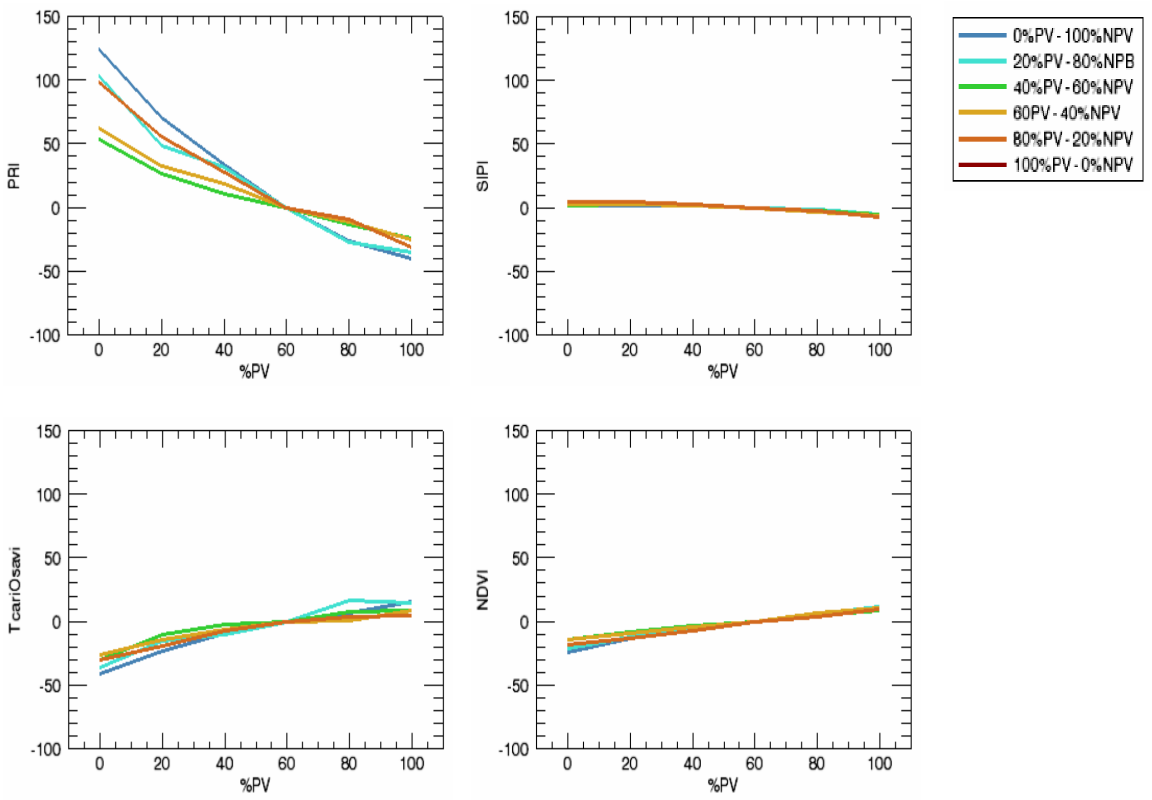

Figure 7. Normalized angular signatures of PRI, SIPI, TCARI/OSAVI *and NDVI calculated from FLIGHT-BRFs for stands various PV-NPV mixtures.*

Based on the above results for each index and for each viewing angle the SD of the PV-NPV mixtures were calculated (Figure 8a). The figure indicates that gNDVI was most sensitive to varying canopy composition, particularly in backscatter direction, followed by PRI and TCARI/OSAVI, respectively. Only SIPI did not show any variability.

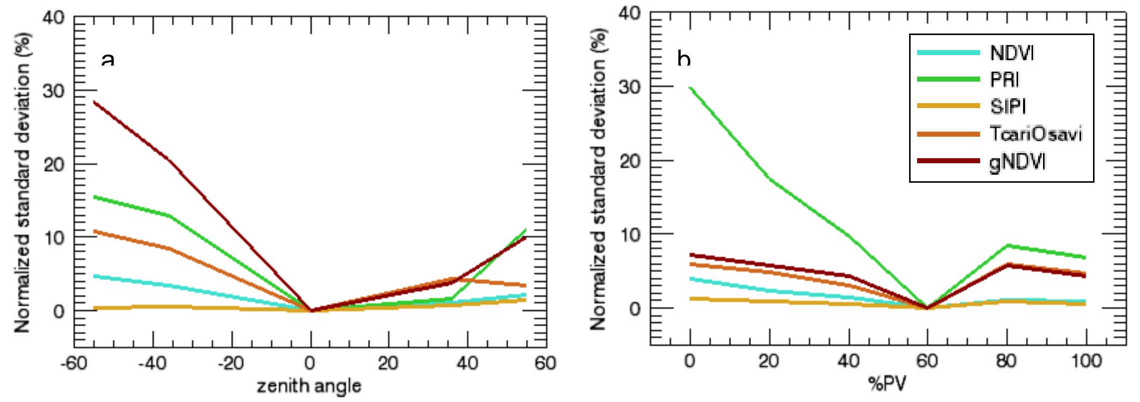

Figure 8. Standard deviations of VIs calculated from the (a) per-angle PV-NPV variability and (b) per-PV-NPV mixture angular variability.

When calculating the SDs of the viewing angles per PV-NPV mixture (the same approach as in figure 4), the SD was greatest for PRI (Figure 8b). TCARI/OSAVI and gNDVI responded as second and third most sensitive indices - more than NDVI - while again SIPI responded invariantly.

From the SDs presented in both figures (8a) and (8b), a final per-index SD was calculated in case of (a) for variable viewing angles and (b) for variable canopy composition (Table 7). When summing up these two SDs, a per-index value of total spread was generated, enabling a quantitative comparison. This comparison was done by ranking the indices from the largest total SD to the lowest total SD. Based on such ranking the PRI and gNDVI can be labelled as '*extremely*' sensitive, the TCARI/OSAVI can be labelled as '*moderately*' sensitive and SIPI can be labelled as '*insensitive*' to the assessed abiotic and biotic factors.

Index	SD (SD[PV-NPV mixtures per viewing angle])	SD (SD[viewing angles per PV-NPV mixtures])	Summed SDs
PRI	6.97	10.34	17.32
gNDVI	11.74	2.48	14.22
TCARI/OSAVI	4.23	2.26	6.49
NDVI	1.83	1.38	3.21
SIPI	0.52	0.41	0.93

Table 7. Ranked SDs of the in Figure 5 calculated SDs.

CONCLUSIONS

The reflectance properties of individual leaves are insufficient to describe the remotely sensed response of vegetation at canopy scale, as it is rather function of an assemblage of PV and NPV elements that are either sunlit or shaded. It was recognized in recent literature that perturbations due to additional abiotic and biotic factors are the key factors inhibiting successful understanding of the retrieved PRI measure (13, 14).

Triggered by the above studies, this work attempted to evaluate at canopy level the fidelity of PRI compared to other chlorophyll indices as estimators of chlorophyll content or photosynthesis-related processes. The influences of variable sun-target-sensor geometry and canopy composition on the indices were assessed from ground-based and spaceborne hyperspectral data over alpine meadow and montane coniferous forest, respectively. Combining the findings of the both studies led to the following conclusions:

- **PRI** responded extremely sensitively to sun-target-sensor geometry and canopy structure. Caution is, therefore, recommended when interpreting PRI estimates. In heterogeneous natural canopies, with a mixture of PV-NPV elements, PRI becomes less effective as indicator of chlorophyll-related processes (e.g., LUE, stress or fluorescence indication). Also, a BRDF correction is desired when using PRI in multitemporal studies.
- **gNDVI** responded extremely sensitively to the variances in case of the alpine meadow. The observed steep slopes and oscillating diurnal behaviour considerably weakened the fidelity of this index.
- In the meadow case **TCARI/OSAVI** was found to be relatively highly sensitive to shaded vegetation. With FLIGHT the TCARI/OSAVI varied twice as much as NDVI. The overall impression arises conclusion that this index has a fidelity that is in-between the gNDVI and NDVI.
- **SIPI** responded rather insensitively to variability in canopy composition and variability in sun-target-sensor geometry. Nevertheless, this invariance raises questions how accurately SIPI is capable to track chlorophyll variation.

It was shown in both case studies that particularly PRI and gNDVI, but also TCARI/OSAVI, were influenced by external abiotic and biotic factors. This lack of fidelity at canopy level suggests that the general applicability and performance of selected chlorophyll indices should be still tested. Therefore, prior to developing new indices further research on the behaviour of existing indices is desired. In particular, attention should be paid to investigate how much variability in the measures is explained by pigment variability itself and how much by additional factors. Then a follow-up work should be devoted to develop for each index a quality assessment such as the degree of confidence. Such an indicator should be provided jointly with the retrieved chlorophyll map.

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