Angular sensitivity analysis of vegetation indices derived from CHRIS/PROBA data

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Abstract

View angle effects present in spectral vegetation indices can either be regarded as an added source of uncertainty for variable retrieval or as a source of additional information, enhancing the variable retrieval; however, the magnitude of these angular effects remains for most indices unknown or unquantified. We use the ESA-mission CHRIS-PROBA (Compact High Resolution Imaging Spectrometer onboard the Project for On-board Autonomy) providing spaceborne imaging spectrometer and multiangular data to assess the reflectance anisotropy of broadband as well as recently developed narrowband indices. Multiangular variability of Hemispherical Directional Reflectance Factor (HDRF) is a prime factor determining the indices’ angular response. Two contrasting structural vegetation types, pine forest and meadow, were selected to study the effect of reflectance anisotropy on the angular response. Calculated indices were standardized and statistically evaluated for their varying HDRF. Additionally we employ a coupled radiative transfer model (PROSPECT/FLIGHT) to quantify and substantiate the findings beyond an incidental case study. Nearly all tested indices manifested a prominent anisotropic behaviour. Apart from the conventional broadband greenness indices [e.g. Simple Ratio Index (SRI), Normalized Difference Vegetation Index (NDVI)], light use efficiency and leaf pigment indices [e.g. Structure Insensitive Pigment Index (SIPI), Photochemical Reflectance Index (PRI) and Anthocyanin Reflectance Index (ARI)] did express significant different angular responses depending on the vegetation type. Following the quantification of the impact, we conclude that the angular-dependent fraction of non-photosynthetic material is of critical importance shaping the angular signature of these VIs. This work highlights the influence of viewing geometry and surface reflectance anisotropy, particularly when using light use efficiency and leaf pigment indices.

Keywords: Vegetation indices; Multiangular remote sensing; Narrowband indices; Light use efficiency; Coniferous canopy; Reflectance anisotropy; Photochemical Reflectance Index

1. Introduction

Spectral vegetation indices (VIs) are designed to assess vegetation photosynthetic activities, leaf area, biomass and physiological functioning (Myneni et al., 1995) on the land surface while reducing the effects of extraneous factors such as background substrate, atmosphere and illumination effects (Vincent, 1997) and so enabling multi-temporal and cross-sensor comparisons (e.g. Goetz, 1997; Lenney et al., 1996). However, it has been demonstrated already that VIs do not only minimize but, in fact, can also exaggerate impacts of solar zenith and view angle (Jackson et al. 1990; Kimes et al., 1985; Pinter et al., 1987). VIs do suffer from directionality not only because of the reflectance anisotropy of surfaces due to vegetation type, canopy structure, non-photosynthetic material, background contributions and shadowing (Kimes et al., 1985; Leblanc et al., 1997; Qi et al., 1995), but also because of the inherent viewing geometry of (large swath) sensors. The Normalized Difference Vegetation Index (NDVI), the most frequently used index in remote sensing applications, usually has higher values at larger viewing angles than at nadir position (Huete et al., 1992; Jackson et al., 1990; Pinter et al., 1987). Typically, over vegetation canopies near infrared (NIR) photons are more...
affected by multiple scattering than red photons that cause an increase of the spectral contrast between the NIR and red band (Kimes, 1983). In addition, surface reflectance anisotropy affects the relationship of red and NIR reflectance values, resulting in slightly varying directional responses per vegetation type (Leblanc et al., 1997; Qi et al., 1995). Also for other indices, such as the Soil Adjusted Vegetation Index (SAVI) and the Global Environmental Monitoring Index (GEMI), similar patterns for various vegetation types were observed with higher values at off-nadir angles than at nadir position (Gemmell & McDonald, 2000; Huete et al., 1992). These and other studies (e.g. Deering et al., 1999) demonstrated that broadband indices are equally dependent on variations in sun–earth-sensor geometry, as in single band measurements, and thus caution is required when using spectral vegetation indices.

One way to cope with the influence of viewing effects is through the development of correction approaches either by following an empirical or a physical logic. Huete et al. (1992) minimized variations in SAVI-view angle response with a simple empirically derived cosine function, although this approach does not allow extrapolation to other indices. A number of methods have been recently proposed using physical Bidirectional Reflectance Distribution Function (BRDF) models to reduce uncertainties caused by sun/view angle and surface variations (Bacour et al., 2006; Csizsar et al., 2001; Huete et al., 2002; Los et al., 2005). For example, the angular concerns and the regional heterogeneity of the surface area of the MODIS VI products are standardized by BRDF models (Schaaf et al., 2002) to produce nadir equivalent reflectance values from which the indices are computed (Huete et al., 2002; Van Leeuwen et al., 1999).

An alternative to minimize the impact of multiangular effects to the status of a source of error is the exploitation of the anisotropic characteristics of the surface for improving indices’ performances. Followers of the multiangular approach advocated that a multiangular viewing improved the performance of indices (e.g. NDVI) for discriminating cover and leaf area index (LAI), when compared to nadir viewing because it explicitly accounts for structural heterogeneity and canopy shading (Diner et al., 1999; Gemmell & McDonald, 2000).

In any case, whether angular effects are treated either as superfluous information or as a source of additional information is only important if the magnitude and significance of the angular variability is assessed, quantified, and finally included in interpretation of the data. Apart from the conventional broadband indices, a notion of the angular response is, for most indices, absent. Particularly for the recently developed narrowband indices, the effect of viewing geometry has not yet been adequately addressed.

Recently developed narrowband indices are often no longer exclusively based on broad spectral bands located in the well-known red and NIR spectral regions but are found anywhere within the 400 to 2500 nm wavelength range having typically a spectral resolution of 2 to 15 nm. Many of these indices originate from studies on specific absorption features of pigments and structure in single leaves [e.g. Photochemical Reflectance Index (PRI)] and were, with the advent of spaceborne imaging spectrometry (Ustin et al., 2004), upscaled to canopy level (e.g. Asner et al., 2004; Nichol et al., 2000, 2002; Peñuelas & Inoue 2000; Rahman et al., 2001). These indices possess the capability to assess – formerly undetectable – biochemical and biophysical properties such as variation in photosynthetic Light Use Efficiency (LUE) (e.g. Gamon et al., 1997; Peñuelas et al., 1995; Stylinski et al., 2002; Trotter et al., 2002), which is a primary driver of Net Primary Production (NPP) and thus ecosystem functioning (Monteith, 1972). To date only a small subset of narrowband indices has been systematically tested at canopy level (e.g. He et al., 2006; Schlerf et al., 2005; Xavier et al., 2006; Zarco-Tejada et al., 2005), and even less were tested on their directional response. This lack of directional testing limits the potential use of the vegetation indices for consistent and accurate long-term monitoring of vegetation on larger to global scales.

The objective of this work is to assess and consistently compare on a statistical basis the magnitude of reflectance anisotropy of commonly used spectral reflectance indices. Further some of the key factors governing the reflectance anisotropy have been identified and investigated using a coupled Radiative Transfer Model (RTM). The selected indices are categorized into broadband and narrowband greenness, light use efficiency and leaf pigments. Because reflectance properties of land surface are anisotropic in nature, indices are assumed to be sensitive to changing viewing angles depending on the spectral bands used and the degree of surface anisotropy present in the observed scene. The pushbroom CHRIS (Compact High Resolution Imaging Spectrometer) sensor mounted on the PROBA (Project for On-Board Autonomy) platform offers a unique availability of continuous spectral bands and multi-angular views from space. This wealth of data enabled the assessment of the angular variability for a wide range of broadband and narrowband indices, exemplified over two Alpine vegetation types exhibiting different degrees of reflectance anisotropy.

2. Data

2.1. Study site

The test site for this study 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) at an average altitude of about 1900 masl. The south-facing slope of the Ofenpass valley floor is considered as the core test site and has long been a subject to ecological studies (e.g. Kötz et al., 2004) and described extensively (Schaepman et al., 2005). Two dominant subalpine ecosystems characterized by contrasting anisotropy features (Koetz et al., 2005), being an old-growth coniferous forest and a meadow, were chosen as vegetation types to assess angular sensitivity.

The evergreen coniferous forest is dominated firstly by mountain pine (Pinus Montana ssp. arborea) and secondly by stone pine (Pinus cembra), being of interest for natural succession. The forest ecosystem can be classified as woodland
associations of Erico-Pinetum mugo. The understory is characterized by low and dense vegetation composed mainly of Vaccinium, Ericaceae, and Seslaraia species. The second vegetation type, a subalpine meadow, can be characterized as poor grassland over calcareous soils. The mixed grassland ecosystem belongs to the floristic association Seslerio-Caricetum sempervirentis.

2.2. Satellite data

The CHRIS sensor on PROBA provides co-registered, spectral contiguous bands at 17 m ground sampling distance, in the spectral wavelength range from 415 nm to 1050 nm. PROBA is an experimental ESA space platform which enables the sensor to capture images from five viewing angles. CHRIS Mode 3 (Land) data were acquired over the SNP on 2004-06-27, 10:41 AM, under partly cloudy conditions (1/8th cloud cover) and low aerosol conditions (Aerosol Optical Depth (AOD) <0.086 at 412 nm, <0.022 at 862 nm). Data specifications are shown in Table 1 (right) and the viewing geometry is shown in Fig. 1 (left). Solar position can be regarded as constant for all five CHRIS Fly-by Zenith Angles (FZA), since the time difference between first and last recording during the satellite overpass was less than two minutes. In the current along-track pointing configuration, the FZA is equivalent to the nominal view angle, which might deviate from the actual observation angle. Actual view angle for the nadir scene was +21.21° in the forward-looking direction (28° off the solar principal plane). FZA +36° was acquired exactly in the solar principal plane. FZA +55° differed only 14° from the solar principal plane and is further referred as forward-scatter. The backscatter angles of FZA −36° and FZA −55° differed 53° and 45°, respectively, from the solar principal plane and lie in backscatter direction.

The CHRIS image set was geometrically and radiometrically corrected following an approach dedicated for rugged terrains (Kneubühler et al., 2005). The geometric correction relies on a parametric approach taking into account the viewing geometry, and geometric distortion due to the sensor, platform and topography. Atmospheric correction of the CHRIS radiance data was performed using the physically based radiative transfer model ATCOR-3 (Richter, 1998), which is based on MODTRAN-4. ATCOR-3 enables the processing of data from tilted sensors by accounting for varying path lengths through the atmosphere, varying transmittance and for terrain effects by incorporating digital terrain model (DTM) data and their derivatives (slope and aspect, sky view factor and solar illumination) (Richter & Schläpfer, 2002). One particularity of this approach is that ATCOR-3 corrects for path scattered radiance and adjacency effects, however not for hemispherical irradiance. The ATCOR-3 generated ‘surface reflectance’ is therefore representing Hemispherical Directional Reflectance Factor (HDFR), following the reflectance terminology of Schaepman-Strub, Schaepman, Painter, Dangel, and Martonchik (2006).

The evaluated accuracy of the acquisition geometry of CHRIS/PROBA in the core of the Ofenpass test site after preprocessing resulted in a geolocation uncertainty for nadir and off-nadir scenes of 0.5–1 pixels (Kneubühler et al., 2005). All preprocessing efforts of CHRIS data finally resulted in geocorrected HDFR data with a spatial resolution of 17 m. The core test site was located in the scene centre line of each scene, implying that cross-track effects could be considered as negligible.

A cloud present above this site, particularly when observed from the +55° FZA, was masked out for all scenes, considerably limiting the inclusion of a number of potential forest pixels at lower slopes.

3. Methods

Amongst the most commonly used indices, we selected those that fit the wavelengths, or closely approach, the centre wavelength positions of the spectral resolution of CHRIS Land Mode 3 (Fig. 2). The VIs were calculated using the remote sensing software package ENVI (ITTVIS, Boulder, CO, USA). Calculated indices were subsequently standardized and studied for their angular effects by means of an Analysis of Variance Repeated Measurements (ANOVA RM) and an independent sample students’ t-test.

The indices listed in Table 2 were selected to be calculated from multiangular CHRIS HDFR data. We use four general
categories of VIs according to their plant physiological functioning: (a) broadband greenness VIs (1–3), being measures of the overall amount of photosynthetic material in vegetation; (b) narrowband greenness VIs (4–6), being measures of the overall amount and quality of pigment content in vegetation; (c) Light Use Efficiency (LUE) VIs (6–9), being measures of the

![A typical canopy reflectance (438–1035 nm) of Swiss pine forest from the CHRIS sensor with its respective bandwidths (Mode 3).](https://www.chris-proba.org.uk/mission/bandsets2.html)

Table 2
Overview of selected vegetation indices

<table>
<thead>
<tr>
<th>Index</th>
<th>Formula</th>
<th>Description</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Broadband greenness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 NDVI, Normalized Difference Vegetation Index</td>
<td>(\frac{(R_{\text{NIR}} - R_{\text{RED}})}{(R_{\text{NIR}} + R_{\text{RED}})})</td>
<td>Measure of green vegetation cover. (CHRIS mid: (\text{NIR}=781\ \text{nm}, \text{red}=672))</td>
<td>Tucker (1979)</td>
</tr>
<tr>
<td>2 SRI, Simple Ratio Index</td>
<td>(R_{\text{NIR}}/R_{\text{RED}})</td>
<td>Measure of green vegetation cover. CHRIS mid: (\text{NIR}=781\ \text{nm}, \text{red}=672)</td>
<td>Tucker (1979)</td>
</tr>
<tr>
<td>3 ARVI, Atmospherically Resistant Vegetation Index</td>
<td>(\frac{(R_{\text{NIR}} - (2R_{\text{RED}} - R_{\text{BLUE}}))}{(R_{\text{NIR}} + (2R_{\text{RED}} - R_{\text{BLUE}}))})</td>
<td>Similar as NDVI while being less sensitive to aerosol effects (CHRIS mid: (\text{NIR}=781\ \text{nm}, \text{red}=672, \text{blue}=490))</td>
<td>Kaufman and Tanre (1992)</td>
</tr>
<tr>
<td><strong>Narrowband greenness</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 NDVI\textsubscript{705}, red edge Normalized Difference Vegetation Index</td>
<td>(\frac{(R_{750} - R_{705})}{(R_{750} + R_{705})})</td>
<td>Leaf chlorophyll content (CHRIS mid: (R_{703}; R_{748}) nm)</td>
<td>Gitelson and Merzlyak (1994)</td>
</tr>
<tr>
<td>5 mSRI\textsubscript{705}, modified red edge Simple Ratio Index</td>
<td>(\frac{(R_{750} - R_{443})}{(R_{705} + R_{443})})</td>
<td>Narrowband SRI, compensates for high leaf surface (specular) reflectance (CHRIS mid: (R_{442}; R_{703}; R_{748}) nm)</td>
<td>Sims and Gamon (2002)</td>
</tr>
<tr>
<td>6 mNDVI\textsubscript{705}, modified red edge Normalized Difference Vegetation Index</td>
<td>(\frac{(R_{750} - R_{705})}{(R_{750} + R_{705} - R_{443})})</td>
<td>Narrowband NDVI, compensates for high leaf surface (specular) reflectance (CHRIS mid: (R_{442}; R_{703}; R_{748}) nm)</td>
<td>Sims and Gamon (2002)</td>
</tr>
<tr>
<td><strong>Light use efficiency</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 PRI, Photochemical Reflectance Index</td>
<td>(\frac{(R_{531} - R_{570})}{(R_{531} + R_{570})})</td>
<td>Index of photosynthetic radiation use efficiency. Sensitive to carotenoid/chlorophyll ratio (CHRIS mid: (R_{530}; R_{570}) nm)</td>
<td>Gamon et al. (1992)</td>
</tr>
<tr>
<td>8 SIPI, Structure Insensitive Pigment Index</td>
<td>(\frac{(R_{660} - R_{453})}{(R_{660} + R_{705})})</td>
<td>Carotenoid/chlorophyll a while decreasing sensitivity to variation in canopy structure (CHRIS mid: (R_{442}; R_{703}; R_{748}) nm)</td>
<td>Penuelas et al. (1995)</td>
</tr>
<tr>
<td>9 RGRI, Red Green Ratio Index</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 ARI, Anthocyanin Reflectance Index</td>
<td>((R_{550})^{-1} - (R_{700})^{-1})</td>
<td>Leaf anthocyanins content (CHRIS mid: (R_{551}; R_{703}) nm)</td>
<td>Gitelson et al. (2001)</td>
</tr>
</tbody>
</table>

\(R\), reflectance. CHRIS\textsubscript{mid} denotes the centre of the used CHRIS bands in Mode 3 (http://www.chris-proba.org.uk/mission/bandsets2.html). The wavelengths in the Formula column stand for the original proposed VI wavelengths, while the wavelengths in the Description column stand for the CHRIS wavelengths that approached closest to the original proposed wavelengths.
efficiency with which vegetation is able to use incident light for photosynthesis, and (d) leaf pigment VI (10), being a measure of stress-related pigments present in vegetation. In case an index could not be calculated for a certain scene pixel (e.g. because of cloud cover, or non-vegetation cover), such a pixel was not included in the study. After pixel cleaning indices values for 353 meadow pixels for the 5 scenes were collected, whilst for forest 3488 pixels were collected.

Vegetation indices were calculated from HDRF data for each scene. Even though the atmospherically resistant vegetation index (ARVI) intends to minimize atmospheric effects, we still preferred to apply ARVI on HDRF data. This allowed preserving consistency in the quantitative inter-index evaluation of the angular signatures, and following Santer, Ramon, Vidot, and Dilligeard (2007) in dark dense vegetation (DDV) trends of ARVI are not significantly different from spectral radiance or HDRF data. However, the primary use of ARVI is for top-of-the-atmosphere radiance data (Kaufman and Tanré, 1992), while in this case we use the DDV approximation to justify the use of ARVI derived from HDRF. In all other situations than the one above, ARVI must be derived from TOA radiances.

Despite the dedicated atmospheric correction, the impression arose that the extreme topography still exerted influence on reflectance anisotropy and, in turn, on indices’ values. The influence that topographic attributes may have on VIs is discussed in Deng, Chen, Chuvieco, Warner, and Wilson (2007), where many subtle but important variations in topography—vegetation relationships were observed. Since the Alps face an erratic topography which is often paired with changing land cover characteristics, the inclusion of topography might significantly perturb surface reflectance anisotropy. To limit our approach in uncertainty, we decoupled topographic effects from our analysis. Multiple regression analysis assessed stepwise the contribution of topographic attributes, which are slope and solar illumination, to the variability of indices’ values. These attributes accounted for up to 13% of the variations of the indices’ values for each angular scene. To ensure that topographic effects are sufficiently decoupled in further analysis a topographic subset was thresholded. At the valley floor the topography is relatively flat and smooth consisting of monotonous coniferous forests and patches of uniform subalpine meadow. Restricting the study site to homogenous topographic conditions of the south-facing slope less than 8° and full sunlight conditions (solar illumination >90%), enabled a reduction of topographic influences on the indices’ values to about 3% for meadow and about 2% for forest. Such small correlation coefficients led to the assumption that considered topographical attributes were sufficiently decoupled. Within the remaining forest data pool an equal number of forest pixels and meadow pixels were randomly sampled (#308), ensuring a sound basis for statistical comparison.

Finally, all indices were normalized against their averaged nadir value, so nadir-position values were set at 1. Normalization provided an opportunity to compare statistically the angular shape of the indices within the same magnitude. A coupled RTM (PROSPECT/FLIGHT (Jacquemoud & Baret, 1990, North, 1996) was then applied to assess scale independent and in a physical manner the underlying driving factors governing the angular signatures.

3.1. Statistical analyses

Mean and Standard Error of Mean (SEM) were used to represent angular variability per vegetation type and ANOVA RMs were additionally calculated to compare per index off-nadir values to nadir values. ANOVA RMs were typically used to identify differences for two datasets measured over succeeding steps (e.g. time steps).

Accordingly, comparing the indices’ off-nadir values to the nadir values, the underlying null hypothesis is that there is no effect of angularity. Resultant $F$ values, which are a measurement of distance between individual distributions, will function as an angular sensitivity indicator. If the null hypothesis is correct then $F$ is expected to be about 1, whereas a ‘large’ $F$ value indicates a larger between-viewing-angle variance than a within-viewing-angle variance, and can thus be interpreted as being an angular effect. Given the assumption that a forest pronounces a higher anisotropy and is spatially more heterogeneous than a meadow, then it is of interest to verify how this reflects in magnitude of the $F$ value. Absolute $t$ values of the independent sample $t$-test provide a likewise measure of the (dis-) similarity of the angular shapes of both structural types.

3.2. FLIGHT simulations

The Forest LIGHT Interaction Model (FLIGHT) developed by North (1996) is a Monte Carlo numerical ray-tracer simulating photon propagation through a 3-D heterogeneous leaf canopy. The model allows the representation of complex vegetation structures and a correct treatment of multiple scattering within the scene composed of various scatter elements. For 3-D simulations, tree crowns are represented by geometric primitives with defined shapes and positions of individual trees with associated shadow effects. Within each crown envelope foliage is approximated by volume-averaged parameters with optical properties of both leaf and woody scattering elements. Canopy reflectance of a range of forest stands parameterized by field-measured canopy variables and CHRI/PROBA acquisition geometries have been simulated. The FLIGHT parameterization was based on averaged field measurements of four core test sites within the forest. Crowns were represented by cones; the canopy structure and optical specifications are further described in Kötz et al. (2004). The foliage optical properties were modelled by PROSPECT (Jacquemoud & Baret, 1990) coupled with FLIGHT while the spectral properties of the woody parts and understory were characterized by spectrometric field measurements (Kötz et al, 2004). Finally, the BRF output of FLIGHT is compared with the approximated HDRF of the CHRIS/PROBA data. Since the HDRF approximation produced by ATCOR includes a hemispherical and adjacency component, the approximation – at least in its trend – is valid.

4. Results

The assessment of the angular sensitivity of the two considered structural canopy types required similar topographical conditions and normalization of the angular shapes to a reference level. Intra- and inter-angular statistical comparisons
enabled subsequently good validation of the directional performance of the considered indices.

4.1. Assessment of angular sensitivity

The key feature in the statistical comparison exercise is the assessment of the angular response of the indices; however the true biophysical impact of this is not assessed in this study. The angular dynamics of the vegetation indices in response to meadow and forest are shown in Figs. 3 and 4 respectively. These figures show the nadir-normalized averaged values for the sampled pixels including ±1 Standard Error of Mean (SEM). As a reference the nadir value is plotted, which is 1, or −1 in case of PRI. Note that directional effects are most extreme in the solar principal plane (Myneni et al., 1997) implying that it should be taken into account that the

Fig. 3. Averaged angular VIs values (normalized against its averaged nadir value) from meadow reflectance values. X-axis denotes viewing angles (negative angles are in back-scattering direction, positive angles are in forward-scattering direction). Y-axis denotes normalized VIs. The error bars shown are ±1 SEM. Angular values were compared with nadir values by means of ANOVA RMs: significance levels: *p<0.05, **p<0.01, *** p<0.001.
maximum angular variability is most likely not reached in this study.

Because of normalization and rescaling the values of some indices, typically operating at smaller ranges (e.g. nadir-average PRI around $-0.02$, nadir-average ARI around 0.007), are dramatically expanded. For others operating at around 1 or higher (SRI, ARVI, mSRI$_{705}$, SIPI, RGRI) normalization implied diminishing of actual values. For the sake of consistent interpretation, the graphs should be interpreted in combination with their statistical analysis. ANOVA RM's results are shown graphically in Figs. 3 and 4; $F$ values of calculated ANOVAs are presented in Table 3. Apart from mSRI$_{705}$ and mNDVI$_{705}$, the indices exhibited significant differences for the two vegetation types.

4.2. Statistical results

ANOVA RM $F$ values (4 off-nadir subsets, each compared to the nadir subset; subset = 308 pixels), shown in Table 3, were used.
to evaluate the magnitude of the angular variability compared to nadir values. Based on this small-scale statistical exercise with 2 vegetation types, the traditional broadband indices NDVI and SRI, NDVI705 and ARI yielded the highest values for both structural types, especially forest, (in general: $F > 106; p < 0.001$) and can therefore be considered as most sensitive to changing viewing angles. Regardless of the apparently greatest angular response shown by the PRI graphs (Figs. 3g and 4g), the $F$ values for forest expressed relatively small numbers ($F$ forest 74.4, $F$ meadow ‘only’ 12.3, see Table 3). In contrast, no significant differences compared to nadir values were found when using $m$SR705 ($p = 0.761$) and $m$NDVI705 ($p = 0.814$) over forest.

A greater degree of anisotropy (forest) did not always automatically translate into higher $F$ values. In the case of NDVI, $m$SR705, $m$NDVI705 and prominently in the case of ARVI a higher $F$ value for meadow than for forest was found. Here, near-nadir position showed a flat response; only when observed under larger viewing angles was the true anisotropy perceived.

Based on the ANOVA’s of the two contrasting vegetation structures, VIs that show, in either case, significant ($p < 0.05$) angular variability (Table 3) will be referred to as ‘anisotropic’, whereas those VIs not revealing a prominent angular behaviour are further referred as ‘Lambertian’, as is the case for $m$SR705 and $m$NDVI705. The VIs were further ranked in Table 4 according to the summed $F$ values of meadow and forest, ranging from displaying primarily anisotropic sensitivity to exhibiting Lambertian behaviour. Regarding the two ecosystems, the SRI, the simplest index, was most sensitive to changing viewing angles, followed by the NDVI705 and NDVI. Because of the resulting low $F$ value above meadow, PRI exhibited the smallest anisotropic behaviour, yet it was still largely significant.

An independent sample student’s $t$-test compared the influence of the two vegetation types on the indices’ angular behaviour. Apart from NDVI, SRI and $m$SR705, the angular response was for all remaining indices vegetation-type dependent (Table 4). The $m$NDVI705 did express significant different angular shapes depending on the structural types; however, as shown earlier, $m$NDVI705 did not express significant angular variability compared to nadir values. The student’s $t$-test indicated that for the remaining narrowband indices and ARVI angular responses were not solely affected by viewing angles, but also by vegetation type. SPl, RGR and PRI yielded the highest student’s $t$ values, indicating that – from the set of tested indices – they were most affected by the contrasting vegetation types.

**Table 3**
Percentages of change compared to nadir values for extreme viewing angles and ANOVA RM $F$ values (off-nadir values compared to nadir values) for meadow and forest

<table>
<thead>
<tr>
<th>Index</th>
<th>$-55^\circ$ nadir meadow $(%)$</th>
<th>$+55^\circ$ vs. nadir meadow $(%)$</th>
<th>$-55^\circ$ vs. nadir forest $(%)$</th>
<th>$+55^\circ$ vs. nadir forest $(%)$</th>
<th>ANOVA $F$ values meadow ($F_{1,614}=\ldots$)</th>
<th>ANOVA $F$ values forest ($F_{1,614}=\ldots$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDVI</td>
<td>7</td>
<td>12</td>
<td>8</td>
<td>8</td>
<td>137.4***</td>
<td>116.3***</td>
</tr>
<tr>
<td>SRI</td>
<td>16</td>
<td>36</td>
<td>18</td>
<td>34</td>
<td>167.3***</td>
<td>200.2***</td>
</tr>
<tr>
<td>ARVI</td>
<td>11</td>
<td>10</td>
<td>13</td>
<td>$-7$</td>
<td>99.9***</td>
<td>10.4***</td>
</tr>
<tr>
<td>NDVI705</td>
<td>4</td>
<td>13</td>
<td>9</td>
<td>16</td>
<td>122.8***</td>
<td>184.1***</td>
</tr>
<tr>
<td>mSR705</td>
<td>3</td>
<td>1</td>
<td>12</td>
<td>$-9$</td>
<td>4.5*</td>
<td>0.097 (p=0.761)</td>
</tr>
<tr>
<td>mNDVI705</td>
<td>2</td>
<td>1</td>
<td>6</td>
<td>$-6$</td>
<td>5.2*</td>
<td>0.05 (p=0.814)</td>
</tr>
<tr>
<td>PRI</td>
<td>$-6$</td>
<td>$-26$</td>
<td>$-32$</td>
<td>$-108$</td>
<td>12.3***</td>
<td>74.159***</td>
</tr>
<tr>
<td>SIPI</td>
<td>$-3$</td>
<td>$-1$</td>
<td>$-2$</td>
<td>11</td>
<td>10.6***</td>
<td>129.126***</td>
</tr>
<tr>
<td>RGR</td>
<td>$-2$</td>
<td>0</td>
<td>$-3$</td>
<td>9</td>
<td>29.6***</td>
<td>59.4***</td>
</tr>
<tr>
<td>ARI</td>
<td>6</td>
<td>40</td>
<td>$-5$</td>
<td>68</td>
<td>106.3***</td>
<td>120.1***</td>
</tr>
</tbody>
</table>

*p < 0.05, **p < 0.01, *** p < 0.001.

**Table 4**
Ranked overview table based on statistical analysis ANOVA RM from most anisotropic to Lambertian (= no significant differences)

<table>
<thead>
<tr>
<th>Index</th>
<th>Summed meadow-forest ANOVA $F$ values</th>
<th>Angular sensitivity</th>
<th>Meadow-forest comparison student’s $t$ and $p$-values</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRI</td>
<td>337.5</td>
<td>Anisotropic</td>
<td>$t=0.444$ ($p=0.657$)</td>
</tr>
<tr>
<td>NDVI705</td>
<td>306.9</td>
<td>Anisotropic</td>
<td>$t=6.519***$</td>
</tr>
<tr>
<td>NDVI</td>
<td>253.7</td>
<td>Anisotropic</td>
<td>$t=-1.154$ ($p=0.249$)</td>
</tr>
<tr>
<td>ARI</td>
<td>226.4</td>
<td>Anisotropic</td>
<td>$t=4.105***$</td>
</tr>
<tr>
<td>SIPI</td>
<td>139.7</td>
<td>Anisotropic</td>
<td>$t=17.280***$</td>
</tr>
<tr>
<td>ARVI</td>
<td>110.3</td>
<td>Anisotropic</td>
<td>$t=-9.232***$</td>
</tr>
<tr>
<td>RGR</td>
<td>89.0</td>
<td>Anisotropic</td>
<td>$t=16.120***$</td>
</tr>
<tr>
<td>PRI</td>
<td>86.7</td>
<td>Anisotropic</td>
<td>$t=-10.488***$</td>
</tr>
<tr>
<td>mNDVI705</td>
<td>5.2</td>
<td>Lambertian</td>
<td>$t=-3.344**$</td>
</tr>
<tr>
<td>mSR705</td>
<td>4.6</td>
<td>Lambertian</td>
<td>$t=-1.919$ ($p=0.055$)</td>
</tr>
</tbody>
</table>

Meadow and forest values were compared with an independent sample student’s $t$-test ($n=1540$). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

5. Discussion of VIs angular responses

The angular behaviour of the single vegetation indices and influential factors are discussed in the next section in more detail. The greenness indices (SRI, NDVI, NDVI705, mSR705, mNDVI705 and ARVI) and the light use efficiency and leaf pigment indices (SPl, RGR, PRI and ARI) are discussed individually.

5.1. Greenness indices

Traditional broadband indices based on red and NIR are known to inherently exhibit anisotropic behaviour, eventually additionally linked to vegetation type or soil conditions (Qi et al., 1995; Leblanc et al., 1997). Indeed, SRI (NIR/red) gave rise to the most pronounced angular variability with the highest values apparent in the extreme forward-scatter direction and the lowest values at nadir position (Figs. 3b and 4b). Measured NDVI shapes (Figs. 3a and 4a) were consistent with earlier studies (Galvão et al., 2004; Huete et al., 1992; Leblanc et al., 1997) and radiative transfer
modelling (Sellers, 1985). The angular shape remained unchanged in the case of the narrowband red edge NDVI (NDVI705) (Figs. 3d and 4d). In contrast, mSRI705 and mNDVI705, which were designed to eliminate the effect of leaf surface reflectance, (Sims & Gamon, 2002) responded in Lambertian fashion to changing viewing angles (Figs. 3e,f and 4e,f). This Lambertian phenomenon can be explained by including the 445 nm reference band, the only modification compared to the NDVI705. The angular distribution of this blue band was rather flat, with a slight decreasing trend in the extreme forward-scatter direction. A similar flattening in the blue was observed by Jin et al. (2002) and Abdou et al. (2006) when using Multi-angle Imaging SpectroRadiometer (MISR) surface BRF products. It was recognized that this phenomenon originates in part from the low values in the blue and uncertainties due to atmospheric correction.

ARVI, designed to minimize atmospheric effects in the sensor output by replacing the aerosol sensitive red wavelength used in the NDVI with a combination of the red and blue wavelength (Kaufman & Tanré, 1992), proved to be symmetrical around nadir for the meadow site (at both sides +10%) (Figs. 3c and 4c). This symmetrical trend was also observed in an earlier study over grass cover (Huete et al., 1992), and therefore a simple cosine adjustment was suggested to correct for viewing effects. ARVI angular response above forest, however, did not reveal a symmetrical trend. The inclusion of the blue band in the algorithm to correct for atmospheric effects flattened values around the nadir position though performed less successfully at large viewing angles.

5.2. Light use efficiency/leaf pigment indices

5.2.1. Photochemical Reflectance Index (PRI)

The measured PRI exhibited a very significant angular anisotropy for both meadow and forest canopies, but it was specifically perceived above forest canopy (Fig. 4g). Average absolute forest PRI values, −0.014 (nadir) and −0.0234 (+55°) (values not shown), were coherent with canopy observation over evergreen shrub species (Stylnski et al., 2002) and with spruce stands (Lewis et al., 2005). The extent to which canopy structure, view and illumination angles are likely to influence the measured PRI values was further investigated based on the FLIGHT model similar to a modelling study by Barton and North (2001).

FLIGHT simulations were carried out considering field measurements taken in the core test site of the Swiss National Park (SNP). Over this site LAI values varied between 1.5 and 4.5, when derived from nadir observations (Kötz et al., 2004). In addition, the woody fraction (ca. 30%) is relatively high because of the advanced age of the pine forest and as forest management practise stopped 70 years ago. Consequently, given the relatively woody stands characterized by gaps between branches and trees, it may be reasonable to expect that observed proportions of Photosynthetic Vegetation (PV) and Non-Photosynthetic Vegetation (NPV) depend on viewing angle. For instance, it is likely that at greater viewing angles lower proportion of PV and a greater proportion of NPV contribute to the observed canopy reflectance. This hypothesis was tested by FLIGHT simulations for which we increased the within-crown NPV proportions as a function of viewing angle (Fig. 5). The resulting angular signature of the PRI based on the simulated BRF produced a concave shape similar as observed by CHRIS (Fig. 4). However, the PRI showed a convex shape when FLIGHT was parameterized with constant PV/NPV proportions for all view angles. Similar observations were published in the study of Barton and North (2001).

Shadow is a further key factor in affecting the anisotropy of forest canopies (Gerard & North, 1997) and therefore the angular response of VIs. The shadowed canopy (forward-scattering values) demonstrated an unequivocally larger PRI drop (−108%) than the sunlit canopy (back-scattering values: −32%), which implies that shadow effects are prevalent in the PRI response. However, since a drop is apparent at both sides around nadir, one can conclude that shadow is not the prime driving factor.

The presented RTM simulations demonstrate that an index exclusively sensitive to leaf photosynthesis activity will be substantially distorted, both spatially and directionally, by the contribution of NPV present in a canopy pixel (e.g. branches, trunks). Indeed, in the spatial domain, variations in NPV and background reflectance affect the performance of greenness VIs (e.g. NDVI, SRI) (Asrar et al., 1992; Baret & Guyot, 1991; Goward & Huemmrich, 1992). In the directional domain, it is the viewing angle that determines the proportion of photosynthetic, non-photosynthetic and background compounds that are exposed to solar radiation in that direction. Then, similar to spatial variations, varying NPV fractions along changing angles may equally impose effects on the angular VI signal. For canopies with LAI<5.0, NPV has been shown to impose a significant effect on the canopy reflectance in woody plant canopies (Asner, 1998). This is especially the case in conifer canopies where the primary reflectance compounds (foliage, branches) are systematically organized at the shoot, branch, whirls, and crown level (Malenovský et al., 2008).

![Fig. 5. FLIGHT-simulated angular PRI values (normalized against their nadir value) for a coniferous forest. Viewing geometry is according to CHRIS FZAs (±55, ±36, nadir). Within-crown PV and NPV proportions varied with viewing angle (%NPV = 100−%PV).](image-url)
5.2.2. Structural Invariant Pigment Index (SIPI) and Red Green Ratio Index (RGRI)

Despite its apparent resemblance and flat shape, off-nadir values of SIPI (Figs. 3h and 4h) and RGRI (Figs. 3i and 4i) differed from nadir values (ANOVA RM, \( p < 0.001 \)) and the total angular shape differed for both structural types (student’s \( t \)-test, \( p < 0.001 \)). The differences between both indices revealed only when considering the \( F \) values in Table 3. Whereas forest RGRI \( F \) was twice as large as \( F \) in meadow conditions, in case of SIPI, however, the forest \( F \) was more than ten times larger than the meadow \( F \). The reason this behaviour occurs can be partly explained because SIPI is designed to reduce the impact of leaf surface and mesophyll structure while estimating carotenoids to chlorophyll \( a \). In a coniferous forest, carotenoids were not expected to play an important role but the greater variability of NPV and PV might account for a larger angular variability. The higher SIPI angular sensitivity over forest relative to RGRI can be partly understood because of the averaging of all red (600 nm to 699 nm) and all green (500 nm to 599 nm) channels in the RGRI. Indeed, for a range of varying view angle-specific PV-NPV settings, FLIGHT recorded an averaged relative flattening of \(-160\% \) (SD: 81) in the far back-scattering direction and \(-74\% \) (SD: 25) in the far forward-scattering direction when broadening the spectral range from a centre red band (CHRIS red\(_{\text{mid}} \): 661 nm) and a centre green band (CHRIS green\(_{\text{mid}} \): 551 nm) towards all red and green bands.

5.2.3. Anthocyanin Reflectance Index (ARI)

An Anthocyanin Reflectance Index in the form of \( ARI = (R_{550})^{-1} - (R_{700})^{-1} \) estimates Anthocyanin accumulation in intact senescing and stressed leaves (Gitelson et al., 2001). Whereas reflectance at 700 nm depends solely upon chlorophyll content, reflectance at 550 nm depends on both chlorophyll and anthocyanin content. Pronounced angular responses over meadow and coniferous stands emphasize the large variability that can occur. In backscatter direction values tended to fluctuate around or below nadir, in forward-scatter direction a prominent increase was apparent (Figs. 3j and 4j). Shadow effects and the influence of a likely greater fraction of observed non-photosynthetic material at larger off-nadir sensor view angles are again most likely contributing to the angular response. Due to the inversion of the two wavelengths, a larger decrease of reflectance at 550 nm rather than 700 nm implied a larger contrast and subsequently a rising ARI.

In general, one must be cautious when applying indices at the canopy level, which were originally based and adapted to leaf level observations. At leaf level a decrease in the green reflectance was related to an increase in anthocyanin content, whereas the reflectance in the blue, red and NIR ranges remained basically the same (Gitelson et al., 2001). At canopy level a decrease in green reflectance might have multiple causes; one of which is an increase in anthocyanin content. Woody compounds, litter, shadow, and soil conditions are other driving factors leading to a decrease in the green in a pixel. In turn the feedback on reflectance of these dynamics varies under changing viewing angles.

6. Summary and conclusions

Viewing geometry is a major determinant controlling the spectral behaviour of vegetation canopies and thus affecting the quality of extracted biophysical parameters. The angular responses of four classes of vegetation indices were compared. Evidence from a sparse angular sampling of four off-nadir CHRIS recordings indicates the following:

Nearly all indices manifested a prominent reflectance anisotropy in the two alpine ecosystems. Indices where off-nadir values significantly differed from nadir values were labeled as being ‘Anisotropic’. The traditional SRI, NDVI, NDVI\(_{705}\), and ARI gave sign of greatest angular sensitivity. The greenness indices which use reflectance at 445 nm as a reference wavelength (mSRI\(_{705}\), mNDVI\(_{705}\)) responded rather insensitive and have been labeled as being ‘Lambertian’. Further, an independent sample \( t \)-test showed that, apart from NDVI, SRI and mSR\(_{705}\), most indices did express varying angular shapes depending on the vegetation type. For those indices the specific surface reflectance anisotropy additionally affects the angular responses.

Reflectance anisotropy of broadband indices observed (NDVI, SRI, and ARVI) concurs with earlier observations (Galvão et al., 2004; Huete et al., 1992; Leblanc et al., 1997). Also Light Use Efficiency indices PRI, SIPI, RGRI and ARI gave rise to significant reflectance anisotropy with an emphasis over forest and in forward-scatter direction. FLIGHT simulations showed that structural variability, in terms of the organization of PV and NPV elements, is a key player in shaping the angular signature of PRI. We therefore suggest that when applying a VI designed to assess leaf processes at canopy level, the accuracy of the biochemical parameter mapping can be greatly improved if the fractions of NPV and background (Canisius & Chen, 2007) are being taken into account.

Traditional broadband indices continue to be applied at large-scale analyses of ecosystem monitoring, for example the boreal forests (e.g. Beck et al., 2006; Goetz et al., 2006). Presently a growing fleet of narrow spectral resolution sensors are operational (e.g. MERIS, MODIS, Hyperion, ALI, etc) with capacities to upscale light use efficiency and leaf pigments indices at canopy level over large areas. Furthermore, indices products are increasingly subject to joint multi-temporal (e.g. Telesca & Lasaponara 2006; Xiao et al., 2006) and cross-sensor studies (e.g. Chen et al., 2005; Ferreira et al., 2003).

This work highlights the importance of viewing geometry, and, by relying on the Helmholtz Reciprocity Principle (Magda et al., 2001), also solar geometry inevitably propagating in multi-temporal and multi-sensor studies. Because reflectance properties of the land surface are anisotropic in nature, sun–earth-sensor geometry may create artificial noise imposed upon basically all VIs. Furthermore, spaceborne and airborne sensors with large FOVs (e.g. Hymap: 61.3°, MERIS: 68.5°) are equally subject to within-scene multiangular effects. In turn utmost caution is mandatory when inter-comparing results from an anisotropy-sensitive index acquired under varying sun–earth-sensor configurations for a given land cover type. In the present era of multi-temporal and cross-sensor applications, standardization of vegetation indices is therefore desired to establish confidence in the reliability of its use.
Standardization to correct for sensor-specific characteristics is nowadays achieved by applying cross-sensor translation equations (e.g. Miura et al., 2006; Teillet et al., 1997; Trischchenko et al., 2002; Steven et al., 2003), but a prerequisite to reduce cross-sensor uncertainty is that atmospheric corrections and processing strategies are adequately addressed (van Leeuwen et al., 2006). Standardization to correct for reflectance anisotropy is nowadays achieved by BRDF models from, which VIs normalized to a standard geometry could be computed (e.g. Bacour et al., 2006; Csiszar et al., 2001; Huete et al., 2002; Los et al., 2005). Nevertheless, until now, these advanced approaches have remained restricted to the traditional broadband indices (e.g. NDVI). Now that a wealth of fine-tuned narrowband indices has been developed, evaluation of their compatibility and consistency may be a first step to allow for large-scale and multi-temporal studies.

On the other hand, research on the potential information content inherent to the directional dimension of many VIs regarding surface anisotropy has been largely left aside (however, see Barnsley et al., 1997; Pocewicz et al., 2007). Evidence from the employed work demonstrated that the angular shape of most of the studied indices, particularly narrowband indices, differs depending on the vegetation structural type. It is therefore suggested that exploiting the angular dimension, parallel to the indices’ actual measures, opens opportunities to provide a quick, additional, source of information regarding structural matters. Future work should further investigate how the angular variability of specific indices (e.g PRI, Sipi) independently relates to structural features (e.g. LAI, fraction cover).

Finally, with the advent of having soon more multiangular imaging spectrometers in space, dependence and independence of atmospheric and surface induced anisotropy will gain in importance. On the one side to achieve consistent retrievals of biochemical and biophysical variables at unprecedented accuracies over large swathes, time frames and regions; as well as decreasing the retrieval uncertainty using multiangular approaches. In any case, both approaches will be required simultaneously to allow for a consistent process monitoring of land and water surface properties (Schaepman, 2007). Vegetation indices as discussed in this contribution will then be a major contributor to the measurement of ecosystem changes and disturbance in an operational fashion.

Acknowledgements

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