DIRECTIONAL SENSITIVITY ANALYSIS OF VEGETATION INDICES FROM MULTI-ANGULAR CHRIS/PROBA DATA

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ABSTRACT:

View angle effects present in vegetation indices are either being seen as unwanted information or as an additional source of information. However, the magnitude of these angular effects remains for most indices unknown. We use the ESA-mission CHRIS-PROBA (Compact High Resolution Imaging Spectrometer–Project for On-board Autonomy) providing spaceborne imaging spectrometer and multidirectional data to assess the directional sensitivity of broadband and recently developed narrowband indices. Apart from the illumination and viewing geometry as well as the atmospheric composition, the surface reflectance anisotropy is a prime factor determining indices´ directional response. Two contrasting structural vegetation types, forest and meadow, were selected to study the affect of different land cover types on the indices´ angular response. This work demonstrates that the tested broadband indices (NDVI, SRI, ARVI) as well as the narrowband indices $NDVI_{705}$, PRI, ARI1 & ARI2 were significantly sensitive to angular effects, while other indices (mSR_{705}, $mNDVI_{705}$, SIPI & RGRI) tested invariant to multiple viewing angle observations. The results suggest that caution is required when using some, but not all, indices since angular effects may differently impact the results, finally seriously hampering interpretation.

1. INTRODUCTION

It is generally assumed that vegetation indices emphasize differences in the spectral response for different features while reducing the effects of extraneous factors such as background substrate, atmosphere and illumination and view angle effects (Vincent 1997) and so enabling multi-temporal and multi-sensor comparisons (e.g. Lenney et al. 1996, Goetz 1997). However, regardless of their assumed invariability, studies on broadband indices observed similar directional effects as found in the reflectance measurements. Angular effects could be reduced (Huete et al. 1992) but could also be increased (Pinter et al. 1987). The most commonly used Normalized Difference Vegetation Index (NDVI), for instance, has usually lower values at a nadir viewing geometry than at large view angles, even though the directionality of NDVI depends on many canopy parameters (vegetation type, distribution, soil and understorey). Typically, over vegetation canopies the NIR band is more affected by the multiple scattering than the red band. This effect causes an increase of the spectral contrast between the NIR and red band leading to a larger NDVI for shaded canopy components than for components in direct sunlight. With changing view zenith angles and sun illumination geometry the relative fractions of sunlit and shaded canopy components are varying, The NDVI thus generally increases as the view zenith angle increases, caused by the larger visible fraction of shaded canopy components. (Galvão et al. 2004). 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 (Huete et al., 1992, Gemmell and McDonald 2000). These and other studies (e.g. Qi et al. 1995a, Deering et al. 1999) demonstrated that broadband indices are equally dependent on sun/viewing and vegetation geometry respectively, in single band measurements, and thus caution is required when using such ratios.

One way to cope with the influence of viewing effects is through the development of correction approaches, e.g. by following an empirical or physical logic. Huete et al. (1992) found that the SAVI response was symmetric around nadir for all canopy conditions and sun angles which permit variations in SAVI-view angle response to be minimized with an empirical derived cosine function. By using a physical BRDF model, uncertainties caused by sun/view angle variations could be reduced, e.g. by calculating an Albedo-based NDVI (Qi et al. 1995b), or by deriving an angle-corrected NDVI (Hu et. al. 2000). Nevertheless, the magnitudes of the sun/view angle effects are also target-dependent; the directional properties differ among land cover types, which considerably complicate the correction of directional effects. An alternative to downgrade angular information to the status of unwanted information, is the exploitation of the anisotropic characteristics of the surface for improving indices´ performances. For instance Gemmell and McDonald (2000) found that off-nadir viewing improved the performance of indices (SAVI, NDVI and GEMI) for discriminating cover and LAI, when compared to nadir viewing. Diner et al. (1999) advocated that a multiangular approach was more accurate than a single view angle NDVI-based approach for estimating LAI because it explicitly accounts for structural heterogeneity and canopy shading.

In any case, whether angular effects are treated either as unwanted information or as a source of additional information is irrelevant unless the magnitude of directional variability is

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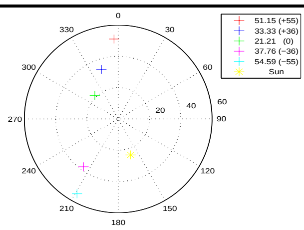
known. Particularly for recently developed narrowband indices directional testing and validation is mostly absent. These ratios of single wavelengths are often no longer exclusively based on bands located in the red and NIR spectral regions. In the last few decades more than 150 spectral vegetation indices have been published in scientific literature, but only a small subset have been systematically tested, and even less were tested on their directional behavior.
The ESA-mission CHRIS-PROBA (Compact High Resolution Imaging Spectrometer-Project for On-Board Autonomy) providing spaceborne imaging spectrometer data of selected targets spread over the world for 5 Fly-by Zenith Angles (FZA) opens opportunities to assess the angular variability for a wide range of narrowband and broadband indices. In this paper broadband and narrowband greenness, light use efficiency and leaf pigment indices were tested subject to their angular sensitivity. Since the tested indices might be also sensitive to vegetation canopy properties (or surface anisotropy), we selected two alpine ecosystems with contrasting anisotropy features (Koetz et al. 2005), being forest and meadow, for comparison.

2. DATA

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. The Ofenpass represents an inner-alpine valley in a high mountainous, rugged terrain with an average altitude of about 1900 m a.s.l. The south-facing Ofenpass forests, where the observations have been made, are dominated by mountain pine (*Pinus Montana*) and stone pine (*Pinus cembra* L.) forest and grazed alpine meadows.
CHRIS Land Mode 3 data were acquired over the SNP on June 27 2004, 10:41h AM, under partly cloudy conditions ($1/8^{th}$ cloud cover). Data specifications are shown in table 1 and the viewing geometry is shown in figure 1. The CHRIS scene has subsequently been geometrically and radiometrically corrected following an approach dedicated for rugged, mountainous terrain, as described in Kneubühler et al. (2005). The core test site of the Ofenpass has a geometric accuracy for the five scenes of 1-2 pixels. The results of the preprocessing of the CHRIS data are geocorrected Hemispherical-Directional-Reflectance-Factor (HDRF) data with a spatial resolution of 17 meters.

Figure1: Polar plot of CHRIS image acquisition and illumination geometry as of June 27, 2004



Sampling	Spectral range
17 m @ 556 km altitude	447-1035 nm

Table 1: CHRIS specifications for Land Mode 3

3. VEGETATION INDICES

The following indices were selected as shown in table 2. Broadband greenness VIs (1-3), being measures of the overall quality of photosynthetic material in vegetation but do not provide quantitative information of any single biophysical or biochemical variable. Narrowband greenness VIs (4-6), being measures of the overall amount and quality of pigment content in vegetation. Light use Efficiency VIs (6-9), being measures of the efficiency with which vegetation is able to use incident light for photosynthesis. Leaf pigment VIs (10, 11), being measures of stress-related pigments present in vegetation. Generally, indices were selected where the wavelengths fit within, or closely approach, the bandwidths of the CHRIS Land Mode 3 range.

	Index	Algorithm	Description	Reference
Broadband Greenness				
1	Normalized Difference Vegetation Index	$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}}$	Measures of the overall amount and quality of photosynthetic material in vegetation	Tucker 1979
2	Simple Ratio Index	$SR = \frac{\rho_{NIR}}{\rho_{RED}}$	Measures of the overall amount and quality of photosynthetic material in vegetation	Tucker 1979
3	Atmospherically Resistant Vegetation Index	$ARVI = \left(\frac{\rho_{NIR} - (2\rho_{RED} - \rho_{BLUE})}{\rho_{NIR} + (2\rho_{RED} - \rho_{BLUE})} \right)$	Similar as NDVI while being less sensitive to aerosol effects	Kaufman and Tanre 1992
Narrowband Greenness				
4	Red Edge Normalized Difference Vegetation Index	$NDVI_{705} = \frac{\rho_{750} - \rho_{705}}{\rho_{750} + \rho_{705}}$	This index was found to show maximum sensitivity to a wide range of chlorophyll contents.	Gitelson & Merzlyak, 1994
5	Modified Red Edge Simple Ratio Index	$mSR_{705} = \frac{\rho_{750} - \rho_{445}}{\rho_{750} + \rho_{445}}$	Narrowband SRI, developed to compensate for high leaf surface (secular) reflectance	Datt 1999
6	Modified Red Edge Normalized Difference Vegetation Index	$mNDVI_{705} = \frac{\rho_{750} - \rho_{705}}{\rho_{705} + \rho_{705} - \rho_{445}}$	Narrowband NDVI, developed to compensate for high leaf surface (secular) reflectance	Datt 1999
Light Use Efficiency				
7	Photochemical Reflectance Index	$PRI = \frac{\rho_{531} - \rho_{570}}{\rho_{531} + \rho_{570}}$	Serves as an index of photosynthetic radiation use efficiency	Gamon et al. 1992
8	Structure Insensitive Pigment Index	$SIPI = \frac{\rho_{800} - \rho_{445}}{\rho_{800} + \rho_{680}}$	Aims to maximize the sensitivity of the ratio of bulk carotenoids to chlorophyll while decreasing sensitivity to variation in canopy structure	Penuelas et al. 1995
9	Red Green Ration Index	Mean of all bands in the red range divided by the mean of all bands in the green range	Attempts to indicate the relative expression of leaf redness caused by anthocyanin to that of chlorophyll	Gamon et al. 1999
Leaf Pigments				
10	Anthocyanin Reflectance Index 1	$ARI1 = \left(\frac{1}{\rho_{550}} \right) - \left(\frac{1}{\rho_{700}} \right)$	Take advantage of the absorption of stress-related anthocyanins	Gitelson et al. 2001
11	Anthocyanin Reflectance Index 2	$ARI2 = \rho_{800} \left[\left(\frac{1}{\rho_{550}} \right) - \left(\frac{1}{\rho_{700}} \right) \right]$	Similar as ARI1 but modified to be less dependent on leaf thickness and density	Gitelson et al. 2001

Table 2: Overview of selected vegetation indices

4. METHODOLOGY

A statistical approach was applied to test the directional sensitivity of the selected vegetation indices based on a random sampling scheme. Due to a cloud covering half the core test sited on the FZA= +55° scene, forest sampling was considerably limited. Furthermore Koetz et al. (2005) suggested a few limiting factors to be considered in data collection, e.g. geolocation errors, errors due to different targets within a pixel contributing to directional signature, variability due to significantly sloping terrain. Pixel sampling was applied on the southern slope of the Ofenpass valley only for those pixels which comprised of, and were surrounded by pixels of meadow and forest features. Meadow field can be considered as a homogenous medium and is located within a slope less than 5%. Encompassing ±60% of the total meadow area within the core test site, 200 pixels were selected. The typical forest occurrence in the Ofenpass valley is characterized by its highly heterogeneous distribution both in terms of tree density and slope factor. Equally 200 forest pixels were randomly selected independently of controlling the above mentioned factors. Such forest variability likely influences its HDRF behaviour; however these two structural types ideally satisfy the intention of comparing two contrasting vegetation geometries.
An ANOVA Repeated Measurements Test was performed to explore whether there is a difference of response per index due to scene viewing angle differences in comparison to nadir values. The test is typically used to identify differences for two datasets over succeeding steps (e.g. time steps). Per vegetation index the four subsequent off-nadir CHRIS data takes were compared with the nadir data.

Accordingly, the assumptions H_0 and H_1 are:
H_0: There is no effect of angularity
H_1: There is effect of angularity.

Apart from assessing angular sensitivity, the influence of canopy heterogeneity on both ecosystems was included by varying the numbers of samples in analysis. As a statistical rule-of-thumb, at least 30 samples are required in parametric tests to approximate a normal distribution. Having 30 pixels as starting point, the ANOVA was carried out iteratively by a stepwise region-growing approach adding randomly each time 10 pixels. The *F* value of the ANOVA, which is 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 'large' *F* indicates an angular effect. Given the assumption that forest pronounces a higher anisotropy and is spatially more heterogeneous than meadow, then it is of interest to verify how this reflects in the continuation of the *F* value.

5. RESULTS AND DISCUSSION

In this study, the actual solar zenith angle for the nadir scene was +21.21° in the forward-looking direction (28° off the solar principal plane). The FZA=+36° was acquired exactly in the solar principal plane, resulting in strong sun glint effects on lake Livigno. The far zenith angle in forward-scatter direction FZA=+55° differed only 14° from the solar principal plane and is therefore, for simplicity, considered as forward-scatter. Similarly the backscatter angles of FZA= -36° and FZA= -55° differed 53° and 45°, respectively, from the solar principal plane and they lie in backscatter direction. The viewing effects observed for reflectance-based indices over forest (a) and meadow (b) are shown in figure 2. The black lines are the average values with standard deviations of the 200 randomly selected pixels, while the grey line represents the nadir value.
All percentages of change are compared to nadir value.

The broadband indices, NDVI, SRI and ARVI, showed a prominent angular variability similar for both forest and meadow with a shape coinciding with earlier observations (e.g. Qi et al. 1995a). In the forward-scatter view zenith (positive view angles), the NDVI and SRI were larger than in the backscatter view zenith (negative view angles).The highest SRI values occurred in the extreme forward-scatter direction (55% and 37% increase from nadir for forest and meadow respectively), minimum values at nadir or close to nadir (-36° in case of forest) and an increase in values in backscatter direction (10% and 14%), being stronger in case of meadow. ARVI, designed to minimize atmospheric effects proved to be symmetric around nadir for both meadow and forest (far backscatter +12%, far forward-scatter +14 (forest) and +17% (meadow)).
The narrowband $NDVI_{705}$, which is a modification of the traditional broadband NDVI, showed a similar trend like its predecessor, i.e. the shape of the curve, though forest demonstrated slightly more dynamics in the greater forward scattering direction (+25%). The mSR_{705} and the $mNDVI_{705}$, comprising of a chlorophyll-invariant ρ_{445} wavelength, performed noticeably less sensitive to viewing angle effects. Especially in case of meadow the angular response was relatively flat. For forest pixels both narrowband indices showed a more pronounced symmetric shape around nadir with similar increases at large forward and backward angles (mSR_{705} : +10% and $mNDVI_{705}$: + 5%).
In the current sampling design, the light use efficiency indices were subject to anisotropy depending on index and vegetation type. Contrary to the other indices, the PRI measured over the forest site expressed a higher response in the extreme backscatter direction (+39%) than viewing in the extreme forward-scatter direction (+7%). However, the near backward scatter direction resembled close to nadir value, while the near off-nadir forward-scatter view zenith did exhibit a stronger response (+12%). SIPI and RGRI, on the other hand, responded rather invariant to directionality in both forest and meadow with a maximum difference comparing to nadir value of solely 3%. Unlike most other indices the RGRI at large viewing angles in meadow exhibited a slight trend towards decreasing values.
From all indices tested on angular effects, the leaf pigments Anthocyanin Reflectance Indices, ARI1 and ARI2, demonstrated the most pronounced variability to oblique view angles. The curves of ARI1 showed a pronounced increase from the backscatter direction to the forward-scatter direction with the exception of the -55° backscatter direction. The large forward-scatter viewing angle gave rise to an increase of 71% and 43% for forest and meadow respectively. Regarding ARI1, note the remarkable difference in shape at far forward-scatter between forest and meadow. Given such vegetation type related differences inferred from oblique views suggests that there lies a potential to capture additional structural-related information as well. However, this angular-structural variability for vegetation indices is currently not well understood.
Having highest values at near forward-scattering, the ARI2 exhibited the most dramatic decreases in off-nadir scan angles in both the forward-scatter and backscatter view zeniths. In backscatter direction, comparing to maximum value, drops were -97% and -133% for forest and meadow respectively, whereas in forward-scatter maximum values dropped with -136% and -115%.

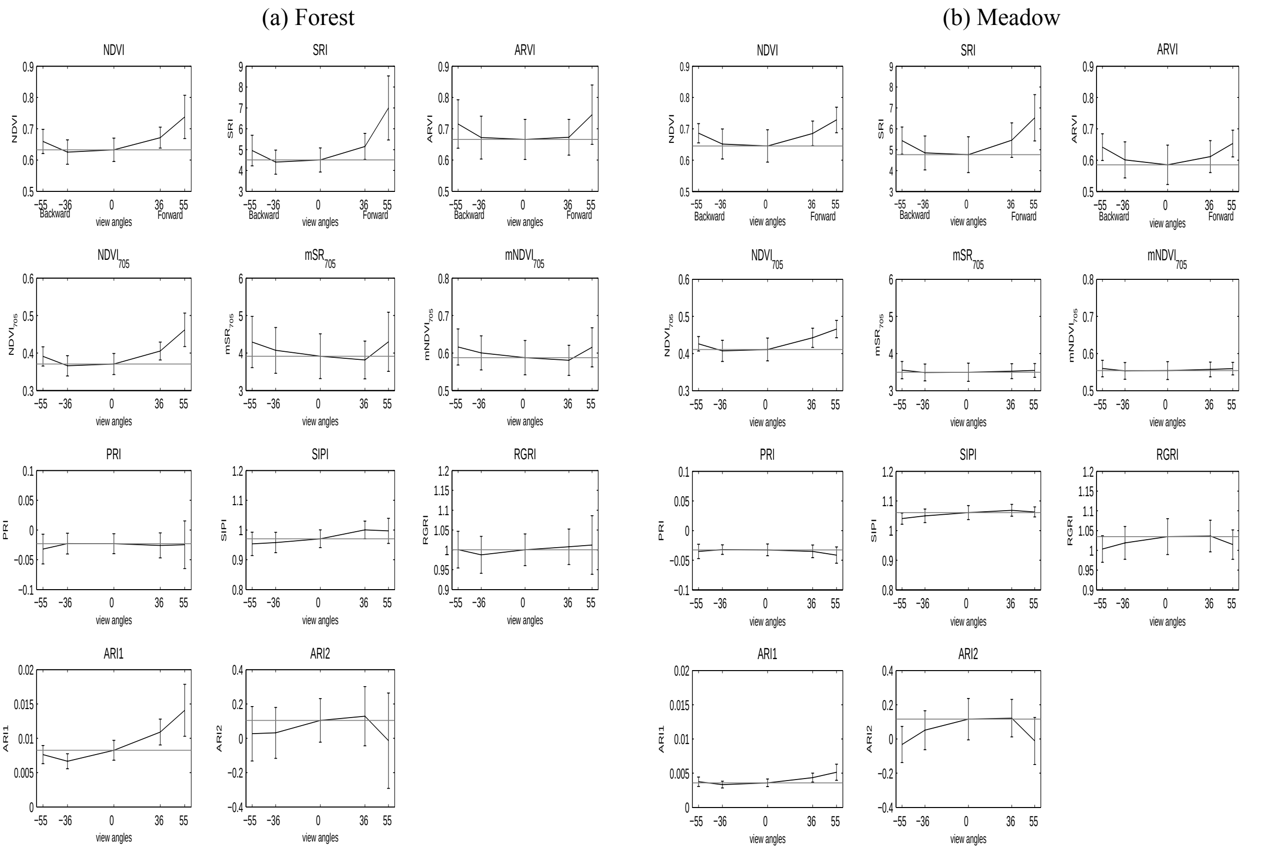


Figure 2: HDRF derived view angle effects of selected vegetation indices for forest (a) and meadow (b) study sites using the CHRIS data. The grey horizontal line indicates the nadir value, the error bars are ±1 Stdev.

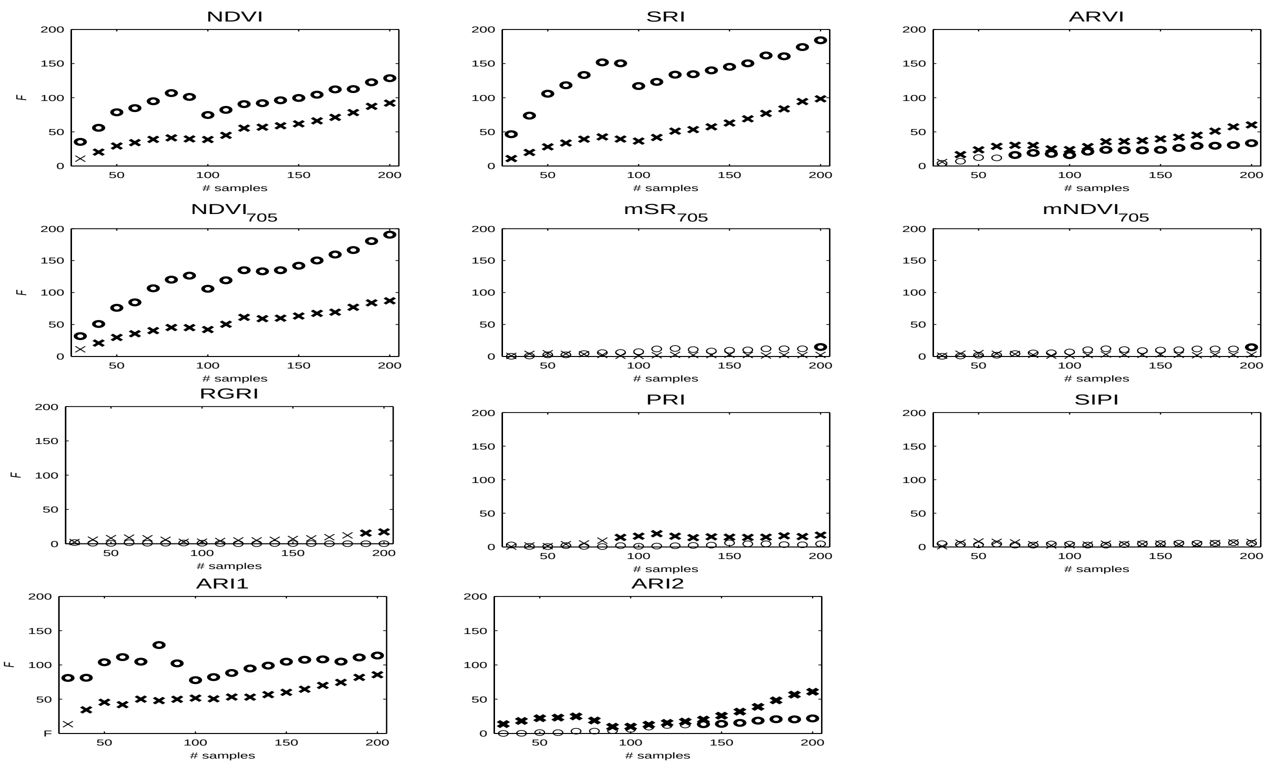


Figure 3: ANOVA *F*-values for a region-growing approach (increment 10 pixels/step) comparing nadir vs. off-nadir measurements. (o) denotes forest, (x) represents grassland. The *F*-values representing significance levels at $p<0.001$ are indicated in bold.

In general, indices measurements over meadow expressed a slightly weaker angular effect than over forest. The indices calculated over the forest site, characterized by large heterogeneity in canopy density and slope differences, were subject to stronger angular effects. More pronounced effects could be found at greater view zeniths due to shadowing and mutual scattering. However apart from the means, the standard deviations were also found larger (e.g. more than double stdev. values for mSR_{705}, $mNDVI_{705}$, PRI and ARI1). The analysis of variance allows statistical assessment to quantify the extent of angular effects. Nadir position was compared with off-nadir values and was subsequently iteratively performed in a region-growing design by adding stepwise 10 samples. This iterative approach was done for all 11 indices and the resulting F-value is shown in figure 3. The differences are considered significant at $p<0.001$ level and are indicated in bold for forest (o) and meadow (x).

The *F*-values indicated well which indices are significantly sensitive to angularity and how obvious these significances take place. Angular sensitivity was evident for broadband indices, especially on forest where the traditional NDVI and SRI showed high *F*-values. The atmospherically corrected ARVI suppressed directional effects compared to the latter, though angular effects remained prominent. In particular, the angular effect was reduced for heterogeneous forest samples where only after pooling 70 pixels significant viewing effects were apparent. When comparing ARVI with NDVI, forest *F*-values decreased on average 4.5 times, while grassland decreased only 1.5 times. Thus indeed the ARVI attempts to correct for atmospheric effects, yet insufficiently to alter statistical significance.

The narrowband $NDVI_{705}$ performed in shape as its broadband counterpart with slightly higher values, especially for forest (overall +32% and only +2% for meadow). No statistically significant differences were revealed for mSR_{705} and $mNDVI_{705}$ unless all 200 forest samples were included; then statistical differences on these indices were apparent (*F* around 14).

The light use efficiency *Structure Insensitive Pigment Index* (SIPI), developed for correcting on structure, proved to perform insignificant along the 200 samples for both structural types. The RPI and RGRI were neither affected by angularity in case of forest, however after 80 (PRI) and 180 (RGRI) samples significant effects - with *F* around 15 - were found on grassland. The angular sensitivity of these indices seems thus not being influenced by strong canopy heterogeneity, as is the case in forest; however other issues might have an influence as well (e.g. varying slope).

Anthocyanin Reflectance Index 1 was tested highly significant already from 30 (forest) and 40 meadow) samples with considerably higher *F*-values for forest. The ARI2, on the other hand, showed to be particularly affected by oblique scenes for grassland, while significant effects for forest took place only after pooling 130 samples and *F* never came higher than 22.

In the end, for most indices the contrasting surface anisotropic properties exerted effects on the directional indices measurements however, not on that extent that it influenced statistics at $p<0.001$ level.

6. CONCLUSIONS

Calculating indices allows for an efficient monitoring of vegetation over large areas. Due to their simplicity ratios derived from reflectance data are traditionally inferred from a wide range of optical sensors under varying environmental conditions and comparisons in time and space are commonly made (e.g. Goetz 1997). However the influence of surface anisotropy and view angle effects have been largely ignored. Furthermore, although not addressed in this work, the behaviour of forward and backscattering due to changing sun zenith angles (e.g., divergence from the reciprocity principle) were shown to give rise to similar directional indices measurements (Huete et al. 1992, Qi 1995a).

Based on pixel sampling over two alpine land cover types, this study demonstrated that viewing geometry can dramatically influence derived vegetation parameters inferred from such indices (e.g. see figure 2; NDVI, AR1, AR2). Regarding the outcome of the statistical tests, the indices are grouped in table 3 based on whether they pronounce directional variability (anisotropic) or remain invariant to changing viewing angles (isotropic).

Index	Directional Sensitivity
NDVI	Anisotropic
SRI	Anisotropic
ARVI	Symmetric (around nadir)
$NDVI_{705}$	Anisotropic
mSR_{705}	Isotropic
$mNDVI_{705}$	Isotropic
PRI	Isotropic/ anisotropic
SIPI	anisotropic
RGRI	Isotropic
ARI 1	Anisotropic
ARI 2	Anisotropic

Table 3: Angular response of selected VIs

Consistent difference in terms of statistics between forest and meadow was found for the *Photochemical Reflectance Index*. Angular variability was never found significant for forest pixels, while variability was evident after including 90 meadow pixels (at $p<0.001$). This result is surprising and not intuitive and contrary to earlier observations. For instance, Barton and North (2001) found with a ray tracing radiative transfer model that particularly this index shows a greater variation of view angle than most vegetation indices. The performance of indices might be affected by a few factors.

- CHRIS channels might be still too broad or not closely enough approaching the wavelength range of the selected narrowband indices.
- In case of forest, the effects of tree density and slope, influencing sunlit and shadowed components at pixel level were not controlled. Highly sensitive narrowband indices might therefore infer large variability. When averaging those pixels, its angular effects might be flattened.

Having noted the above remarks, a number of conclusions can be drawn. Vegetation indices respond differently to viewing angles. All broadband indices tested showed significant anisotropic behaviour, with ARVI having the lowest *F*-values. Depending on the wavelength included, narrowband indices may average out or emphasize viewing angle effects. Further, for some indices tested, such as PRI, statistical differences due to viewing angle were dependent on the land cover type. The same results might be expected for changing illumination angles. However, we propose further research assessing the full angular domain of illumination and viewing geometries. To improve the quantitative comparison of vegetation indices inferred under various viewing geometry it is suggested to introduce a spectrally dependent directional correction factor, taking into account solar and canopy geometry as well.

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