Physical Mechanisms in Hyperspectral BRDF Data of Grass and Watercress

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INTRODUCTION

Numerous studies addressing the bidirectional reflectance distribution function (BRDF) of vegetation canopies and bare soils have shown that most surfaces reflect incoming radiance anisotropically (Kriebel, 1978; Kimes et al., 1986; Deering, 1989; Deering et al., 1992). Today, the significance of BRDF effects is well recognized, and various surface bidirectional models have been developed, especially for vegetated canopies. These models enable the use of reflectance anisotropy for extracting surface information from remote sensing data (e.g., Walthall et al., 1985; Verstraete et al., 1990; Roujean et al., 1992).

Still, in spite of a tremendous increase in BRDF literature in recent years, a small amount of results have been published on the spectral dependence of the bidirectional phenomenon. Current research has devoted much effort to the understanding of BRDF as a function of viewing and illumination geometries (Deering et al., 1992; Ranson et al., 1994), but few investigations have addressed the spectral properties of reflectance anisotropy. Likewise, most of the presently available BRDF models do not explicitly handle the spectral variability of BRDF effects.

With the planned launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Multispectral Imaging Spectroradiometer (MISR) on NASA’s Earth Observing System (EOS) platform in 1999 the spectral variability of reflectance anisotropy has to be taken into account. These two sensors will provide bidirectional data from space over a wide range of the electromagnetic spectrum. While MISR is specifically designed to acquire bidirectional data from nine cameras along-track in four visible and near-infrared bands, MODIS with a viewing swath of 2330 km will capture BRDF effects across-track in 36 bands ranging from 0.4 μm to 14 μm. Proper use of MODIS and MISR imagery, along with data from other EOS instruments, will require a thorough understanding of spectral BRDF effects. Therefore, hyperspectral data
analysis techniques, mainly developed for one-directional remote sensing data, have to be closely linked with the upcoming BRDF research.

This study focuses on the physical mechanisms driving the spectral dynamics of bidirectional reflectance effects. Two vegetated targets, an erectophile grass lawn and a planophile watercress canopy, measured under controlled laboratory conditions serve to validate the theoretical concepts of BRDF effects.

**PHYSICAL MECHANISMS**

**Canopy Geometry**

As recently confirmed by a study of Hapke et al. (1996), bidirectional reflectance effects in vegetation canopies are primarily caused by the distribution of shadows, observed under a specific viewing-illumination geometry and a given sensor’s field of view. The composition of shadowed and illuminated canopy components is highly dependent on leaf orientation distributions and other structural properties, which are influenced by plant species, phenology, and health conditions. According to Kimes (1983), the influence of canopy geometry on BRDF can be explained mainly by two effects: the gap and the backshadow effects.

In an erectophile canopy, the orientation of leaves allows views of the lower, less illuminated canopy levels (gap effect). Changing either the viewing or illumination direction has a strong influence on the reflectance since the proportions of shadowed and illuminated constituents are also changed. If only the gap effect were present in a dense erectophile vegetation canopy (i.e., no soil surface contributions), the lowest reflectance values would be measured in the nadir direction since with increasing view zenith angles only the well-illuminated top layers of the canopy are observed. The BRDF shape would result in an azimuthally symmetric bowl centered around the nadir value.

However, with the backshadow effect, most vegetated surfaces tend to have their minimum reflectance slightly shifted to the forward scatter direction. Pointing towards the illumination direction, the sensor views the unilluminated, shadowed leaf surfaces. In addition, a higher proportion of canopy components with normals pointing away from the illumination direction is observed in the forward scatter direction. Due to the cosine law, these canopy facets are less illuminated. If only the backshadow effect were operating, the lowest reflectance for a dense erectophile canopy with opaque facets would be measured at the most extreme view zenith angle in the forward scatter direction. But since leaves are not typically opaque, their transmittance properties reduce the impact of the backshadow effect, and, under extreme viewing angles, the gap effect becomes dominant. As a combination of gap and backshadow effects, densely vegetated erectophile canopies produce a minimum reflectance near nadir in the forward scatter direction, a reflectance maximum (or “hot spot”) in the backscatter direction, and variously distinct bowl shapes in BRDF characteristics. In addition, in most vegetation canopies some specular reflection occurs and increases the forward scattering component.

The relative influences of gaps and backshadowed facets on canopy reflectance are determined by the source zenith angle and the canopy geometry. Backshadow and gap effects are more likely in vertically oriented erectophile plants such as a grass lawn (Fig. 1a) and are more pronounced at high source zenith angles (Kimes, 1983). A planophile canopy, such as watercress, basically displays the top canopy layer only, hiding the backshadowed facets and the gaps underneath (Fig. 1b). Thus, in general, planophile canopies expose a more isotropic characteristic and a less pronounced hot spot than erectophile surfaces. Planophile canopies, however, are likely to exhibit a stronger forward scattering effect than erectophile surfaces due to the higher specular reflection on horizontally oriented leaves.

**Multiple Scattering**

The “darkness” of the shadow, that is, the contrast between shadowed and illuminated facets, is regulated by the intensity of scattering in a canopy. Radiance reflected or transmitted by leaves into the canopy leads to a diffuse, secondary irradiance that brightens the shadowed areas. Consequently, the contrast between shadowed and illuminated leaves is reduced.

Assuming a constant level of irradiance and a given vegetation canopy geometry, the amount of scattering is determined by the canopy optical properties. With higher reflectance and transmittance (i.e., lower absorbance), more light is available within a canopy for scattering, and the surface reflectance is characteristically more isotropic. In the case of a vegetation canopy, the green and particularly the near-infrared absorbance values are relatively small, resulting in a high amount of multiple scattering and a small reflectance anisotropy. Conversely, the lack of scattering in the red and blue chlorophyll absorbance bands causes high anisotropy. Thus, the optical properties have a critical effect on the BRDF characteristics of a surface.

Concerning the scattering of radiation within a single leaf, Gates et al. (1965) reported that strong spectral variability is not evident. Assuming that the scattering process between canopy components, particularly leaves, is also not highly wavelength-dependent, the spectral dynamics of multiple scattering effects inside a specific canopy are caused by the canopy optical properties only. Furthermore, since reflectance and absorbance characteristics are inversely correlated for most vegetated surfaces, one can adequately relate multiple scattering ef-
effects in a specific canopy to the amount of reflected radiation alone.

**Interrelations**
Camillo (1987) showed through simulations and measurements that canopy architecture and multiple scattering are interrelated. In general, with an increasing number of canopy layers, multiple scattering is also increased. In addition to the leaf optical properties, the relative numbers of layers (or leaf area index) and the geometry of a vegetation canopy will therefore influence the amount of multiple scattering. Contrary to the optical properties, the effect of canopy architecture on multiple scattering is assumed to be spectrally independent.

**EXPERIMENTAL METHODS**
A 60×60 cm area of erectophile grass lawn (*Lolium perenne*) and a planophile watercress (*Lepidium sativum*) canopy of 95×95 cm size served as the main objects for laboratory measurements made in April 1996 at the European Goniometric Facility (EGO) of the Joint Research Center (JRC) in Ispra, Italy. Since both canopies almost completely covered the ground surface area, the soil had little effect on the sensor signal. For comparison reasons a concrete slab of 50×50 cm was also measured.

Most data were taken under an illumination zenith angle of 35°, using a tungsten 1000 W halogen collimated lamp as light source. Bidirectional reflectance data were taken for viewing zenith angles between −75° and +75° over the full azimuth circle. The viewing angle resolution was either 5° and 15° (high resolution) or 15° and 30° (low resolution) in zenith and azimuth, respectively. A GER-3700 spectroradiometer providing hyperspectral resolution of about 1.5 nm in the spectral range between 450 nm and 1000 nm was used as sensor with a field of view of about 3°. Mounted 2 m distance from the targets, an optimal sampling of the bidirectional effects was possible.

Due to sensor problems the full nominal range of the spectroradiometer specified as 400–2450 nm could not be used in this study. The data below 450 nm were too noisy and above 1000 nm a temperature instability in the sensor caused unreliable data. The range between 450 nm and 500 nm has been kept in spite of noise problems due to the importance of the blue absorption for vegetation studies. Around 700 nm and 900 nm the sensor temporarily revealed outliers which are excluded in most of the figures presented. A total of 354 channels consisting of valid data between 450 nm and 1000 nm with a spectral resolution of about 1.5 nm were analyzed.

Details on the sensor, laboratory setup, calibration, and data preprocessing can be found in the companion paper by Sandmeier et al. (1998).

**METHODOLOGY**
BRDF data are influenced by the spectral reflectance variability of a target. In order to concentrate on BRDF related effects, in this study all reflectance data are normalized to a standard reflectance signature of the respective targets. By this means, BRDF effects are separated from the underlying target reflectance signature. As a standard reflectance signature, two quantities are eligible: hemispheric reflectance which is defined as the mean reflectance integrated over the hemisphere (Sandmeier et al., 1998), or nadir reflectance. Compared to nadir reflectance, hemispheric reflectance is hard to obtain from remote sensing data, and in many cases, both quantities produce analogous normalization. Thus, we used the more intuitive nadir reflectance as a standard reference:
ANIF(λ,θ,φ,θ,φ)= \frac{R(λ,θ,φ,θ,φ)}{R_0(λ,θ,φ)} \quad \text{[dimensionless]}, \quad (1)

where \( R \) = bidirectional reflectance factor, \( R_0 \) = nadir reflectance factor, \( λ \) = wavelength, \( θ \) = zenith angle, \( φ \) = azimuth angle, \( i \) = illumination direction, and \( r \) = viewing direction.

The anisotropy factor (ANIF) describes the portion of radiation reflected into a specific view direction relative to the nadir reflectance and is sometimes called relative reflectance (Jackson et al., 1990). Thus, throughout this article, the term BRDF is applied to both the original bidirectional reflectance and the nadir-normalized anisotropy factor data.

Comparing hyperspectral reflectance anisotropy properties between different target types, it is sometimes convenient to rely on a single anisotropy quantity per spectral band and target. For this reason, we introduced an anisotropy index (ANIX) defined as the ratio of the maximum and minimum bidirectional reflectance factors acquired in the solar principal plane (or defined azimuth plane) in a spectral band:

\[
\text{ANIX}(λ) = \frac{R_{\text{max}}(λ)}{R_{\text{min}}(λ)} \quad \text{[dimensionless]}, \quad (2)
\]

where \( R_{\text{max}} \) = maximum bidirectional reflectance factor and \( R_{\text{min}} \) = minimum bidirectional reflectance factor.

The anisotropy index (ANIX) gives the amplitude of bidirectional reflectance variation for a given spectral band for a defined view azimuth plane. In most cases, it is an accurate overall estimate for reflectance anisotropy in a given azimuth direction. For the principal plane, \( R_{\text{max}} \) is theoretically measured in the hot spot, whereas \( R_{\text{min}} \) is near-nadir for vegetation surfaces. Because hot spot reflectance cannot be adequately acquired by the goniometer we used, and to avoid relying on interpolated data, the closest measurement to the hot spot was used for \( R_{\text{max}} \) in this study.

**RESULTS AND DISCUSSION**

**Nadir-Normalized BRDF**

Figures 2a–c illustrate nadir-normalized BRDF data, that is, anisotropy factors, over the hemisphere for the grass lawn and the healthy and the dying watercress canopies in a polar coordinate system for four different wavelengths (for an explanation of the coordinate system, refer to Sandmeier et al., 1998). Data for the grass and the healthy watercress were acquired in high angular resolution (\( Δθ_r = 15^\circ \), \( Δφ_r = 15^\circ \)), data for the dying watercress were obtained in low resolution (\( Δθ_r = 15^\circ \), \( Δφ_r = 30^\circ \)) and appear smoother for this reason. The hot spot was interpolated from the adjacent measurements and only suggests a trend of the real situation (Sandmeier et al., 1998). The four wavelengths (blue, 505 nm; green, 550 nm; red, 675 nm; NIR, 725 nm) are chosen to represent the extremes of a continuous change in BRDF shapes over the wavelength spectrum. High reflectance anisotropies are observed in the 505 nm and particularly in the 675 nm range for all three targets. Moderate anisotropy appears at 550 nm, and rather low anisotropy is present throughout the near-infrared range represented by the 725 nm band. A complete sequence of BRDF shapes from 500 nm to 1000 nm can be seen as a movie simulation on a Web site (http://www.geo.unizh.ch/~sandi/BRDF/). In addition, the spectral dynamics of anisotropy in the principal and orthogonal planes are depicted in Figures 3–5 discussed below.

All three vegetation canopies reveal a dominant hot spot in the backscatter direction and are almost symmetrical about the principal plane. The erectophile grass lawn shows the strongest anisotropy and exhibits a steep slope in the forward scattering direction caused by the backshadow effect (Fig. 2a). The BRDF of the healthy watercress is much more symmetric about the nadir than the grass lawn data because the planophile watercress canopy is more dominated by the gap than the backshadow effect (Fig. 2b). In the case of the dying watercress, the individual leaves bent due to water stress and lead to a more erectophile canopy structure. As a result, the backshadow effect is enhanced, and produces an asymmetric bowl shape similar to the BRDF of the grass lawn (Fig. 2c).

**Anisotropy as a Function of Wavelength**

Figure 3 shows bidirectional reflectance factors (BRF) in the principal plane (PP), and anisotropy factors (ANIF) in both principal and orthogonal planes (OP) as a function of wavelength for the grass lawn and the healthy watercress canopy. Figure 4 the corresponding 3-D plots of the same data are given for better comprehension. For reasons of comparison, the dying watercress data are added in Figure 5.

Plots of bidirectional reflectance factors versus wavelength, as shown in Figures 3a–b, are common for demonstrating BRDF effects (e.g., Sandmeier et al., 1995). However, they are underlay by the reflectance signature diluting the spectral characteristics of BRDF effects. The overlap among the individual reflectance spectra from different view zenith angles indicates the spectral variability of BRDF effects. By normalizing BRDF spectra to a reference reflectance signature such as nadir reflectance [Eq.(1)], a systematic analysis of wavelength dependence of BRDF effects becomes possible (Middleton, 1992). Figures 3c–d, which show the anisotropy factors corresponding to Figures 3a–b, confirm the usefulness of normalization. Even in the orthogonal plane (Figs. 3e–f), where BRDF effects are not strongly expressed, a distinct spectral dependence of BRDF effects is observed for both canopies, primarily for the large view zenith angle directions. The 3-D plots in Figure 4 demonstrate the generality of the phenomena.

The spectral variability of reflectance anisotropy is most pronounced in the vertically structured grass lawn.
Figure 2. Anisotropy factors (i.e., nadir-normalized BRDF data) of a) grass, b) healthy watercress, and c) dying watercress in four representative spectral bands. Source zenith angle is 35°. View zenith and azimuth angle resolutions are 5° and 15° for a) and b) and 15° and 30° for c). The hot spot is interpolated using a spherical trigonometric approach (Sandmeier et al., 1998).
Figure 3. Bidirectional reflectance (BRF) and anisotropy factors (ANIF) of grass and healthy watercress in the principal (a–d) and orthogonal planes (e–f) for selected view zenith angles in the visible and near-infrared ranges. Hemispherical reflectance (h.r.) is provided as a reference on all plots. Data presented in panels c–f are taken from the principal and orthogonal planes of data sets given in Figures 2a–b. Source zenith angle is 35°. Outliers at 700 nm are depicted as gaps.
Figure 4. 3-D plots of bidirectional reflectance (BRF) and anisotropy factors (ANIF) of grass and healthy watercress in the principal (a–d) and orthogonal planes (e–f). In Figures 4a–b unsmoothed data, including outliers, are depicted. In Figures 4c–f outliers and missing hot spot data are depicted as gaps, and the data are slightly smoothed by a 3×1 mean filter over the wavelength axis. Angular view zenith and azimuth resolutions are 5° and 15°, respectively.
surface (Figs. 3a,c,e and 4a,c,e) and in the dying watercress data (Fig. 5). The effect is particularly large in the visible part of the spectrum but rather small in the near-infrared. This is in good agreement with the physical explanations in the second section, that the canopy structure and the intensity of multiple scattering inside a canopy are dominating the extent of reflectance anisotropy. The distribution and “amount” of shadows for a given source zenith angle are determined by the canopy geometry and remain the same for all wavelengths, but the “darkness” of the shadows is affected by the spectrally variable multiple scattering. Multiple scattering is high in the near-infrared spectral region due to the low absorbance, reducing the expression of anisotropy as demonstrated in Figures 3e–f and 4e–f for grass and healthy watercress, and in Figures 5a–b for dying watercress. Likewise in the green spectra, where visible reflectance is highest, anisotropy is less pronounced than in the blue and red regions.

As expected, the maximum reflectance appears for all canopies at the measurement closest to the hot spot, which is 35° zenith angle in our case, and the lowest reflectance is slightly shifted to the forward scatter direction (Figs. 2, 3a–d, 4a–d, and 5a). The ANIF spectra obtained at backscatter angles for grass and healthy watercress (Fig. 3c–d) are similar in general characteristics. However, in the forward scattering direction, the spectral regions associated with greater anisotropy are different for these two canopies: Anisotropy is greater in the green spectral region in the grass canopy, but in red and blue regions in watercress. Further measurements are required to explain this. The dying watercress in Figures 5a–b exhibits characteristics similar to the grass lawn, particularly in the visible spectrum. The decay process in the dying watercress apparently modifies the canopy structure from a planophile to an erectophile geometry.

Thus, the gap and particularly the backshadow effects are enhanced, leading to a more pronounced anisotropy similar to the effects seen in the grass lawn.

In the orthogonal planes (Figs. 4e–f and 5b), where the backshadow effect is small, anisotropy is due primarily to the gap effect. Only at extreme view zenith angles, where the gap effect is most dominant, can some anisotropy be observed in either canopy. It can also be seen in Figures 3e–f, 4e–f, and 5b that the BRDF of the grass and the watercress canopies are not fully symmetrical to the principal plane due to their structural heterogeneity. Thus, a complete characterization of BRDF effects of vegetation canopies requires measurements from both sides of the principal plane.

Anisotropy as a Function of Reflectance Intensity

If BRDF effects and canopy spectral optical properties were unrelated, the ratio between reflectance at an arbitrary view zenith angle and nadir reflectance (i.e., the anisotropy factor) would not vary spectrally. Therefore, ANIF plotted versus nadir reflectance intensity should result in straight horizontal lines at the characteristic value for each view angle. However, Figures 3c–f demonstrate a rather strong spectral variability of ANIF data for grass and watercress. In addition, ANIF data (Figs. 3c–f) seem to be associated with spectral variability in nadir reflectance intensity given in Figures 3a–b. This association is confirmed by examining the relative change in ANIF over the observed range of nadir reflectance. Both canopies show that no change in ANIF occurs at relatively high nadir reflectance intensities. However, as nadir reflectance decreases below about 30%, both canopies exhibit significant change in ANIF as a function of nadir reflectance (Figs. 6a–b). The 3-D plots in Figures 6c–d demonstrate the gradual change from high anisotropy dynamics in the spectral regions exhibiting low re-
Figure 6. Anisotropy factors (ANIF) of grass and healthy watercress in the principal plane versus nadir reflectance for wavelengths between 675 nm and 1000 nm. The 3-D illustrations (c–d) are related to Figures 6a–b. The hemispheric reflectance (h.r.) in Figures 6a–b is added for comparison reasons. Outliers and missing hot spot values are depicted as gaps. Angular view zenith and azimuth resolutions are 15° and 30°, respectively. Source zenith angle is 35°.

Reflectance to low dynamics in the spectral regions showing high reflectance. This is in good agreement with the multiple scattering mechanisms described in the second section; the relative expression of anisotropy is determined by the canopy absorbance characteristics and therefore is inversely related to reflectance intensity.

A detailed look at the relationship between reflectance anisotropy and nadir reflectance reveals anomalies most pronounced in the erectophile grass lawn at extreme view zenith angles for wavelengths producing low reflectances (Fig. 7). Referring to the physical mechanisms outlined in the second section, the anisotropy in canopies with nonopaque leaves is influenced by transmittance effects which affect the absorbance and scattering characteristics of the vegetation canopy. The addition of a transmittance component to multiple scattering in vegetation disturbs the relationship between anisotropy and reflectance. Transmittance mainly affects the backshadow effect, which is dominant in the forward scatter direction in erectophile canopies. The grass lawn data (Fig. 7a) is therefore more influenced by the effect than the planophile watercress (Fig. 7b).

As long as transmittance and reflectance are highly correlated, multiple scattering effects can be adequately described by reflectance. Unfortunately, no leaf optical properties have been measured during the laboratory campaign, although a FIFE data set of a Konza prairie grassland (tall dropseed, Sporobulus asper; Strebel et al., 1994) was used to validate this assumption. Even though the reflectance intensity of the Konza grass species is different from the grass lawn of our experiment, the optical properties are comparable and characteristic for most grass species. Figure 8 shows leaf transmittance versus leaf reflectance data for the Konza prairie grass species in four wavelength ranges. In spite of the limited comparability, it appears that the deviation from a linear relationship between transmittance and reflectance is particularly strong in the very low and the very high reflectance/transmittance ranges, and therefore might well be responsible for the anomalies observed in Figure 7 and...
in the high reflecting part of Figure 6. This finding confirms that in addition to canopy architecture, both reflectance and transmittance properties, that is, the absorbance characteristics of a vegetation surface determine multiple scattering effects. Since canopy absorbance is hard to obtain, reflectance measurements are used as a surrogate.

Anisotropy Index (ANIX)

In order to capture reflectance anisotropy in a single quantity, an anisotropy index (ANIX) has been defined in Eq. (2) as the ratio between the highest and the lowest reflectance value per wavelength in the principal plane (or defined azimuth plane). In our case, with an illumination zenith angle of 35°, the grass and the watercress exhibited $R_{\text{min}}$ in the principal plane at a view zenith angle of $-30^\circ$, near the specular direction over most of the spectral range (Fig. 3). The $+30^\circ$ view zenith angle in the principal plane was chosen for $R_{\text{max}}$ to obtain the closest measurement to the hot spot.

Figure 9a shows the ANIX versus wavelength data for five measurement series acquired in the laboratory campaign (compare Sandmeier et al., 1998). In addition to three vegetation canopies previously described, a concrete slab and a second healthy watercress data set (illumination zenith angle=$30^\circ$) are added for comparison reasons. All channels in the range of 500–1000 nm, with the exception of outliers, are depicted without smoothing the data. The concrete slab, the only nonvegetated surface, shows almost no spectral variability in reflectance anisotropy and, with an ANIX of about 1.2, exposes rather isotropic reflectance characteristics. The grass lawn, however, shows a very strong spectral dependence of anisotropy. As seen in Figures 2–4, the low absorbing near-infrared range exhibits the lowest anisotropy, whereas anisotropy is pronounced (ANIX$\leq 3$) in the highly absorbing blue and red spectra. Anisotropy for the green region, where absorbance by chlorophyll is lowest, is reduced compared to the blue and red spectra in some canopies.

A similar condition is given in the dying watercress data, confirming the change of canopy geometry from planophile to a more erectophile structure through the leaves’ decay. The measurements of healthy watercress acquired under two different illumination directions, on the other hand, differ only slightly and exhibit rather low spectral variability. According to Figure 9a, a discrimination between healthy and dying watercress based on BRDF data should be performed in the visible red range.

Figure 7. Anisotropy factors of a) grass and b) healthy watercress in the principal plane for four representative view zenith angles versus nadir reflectance as a zoom section of the low reflecting spectral range.

Figure 8. Leaf transmittance versus leaf reflectance of tall dropseed (Sporobulus asper), a prairie grass species measured during FIFE-89 by Dr. E.M. Middleton, NASA/GSFC, using an SE590 spectroradiometer (Strebel et al., 1994).
and, in contradiction to conventional techniques, not in the low absorbing near-infrared range.

Figure 9b shows the same ANIX data as in Figure 9a but plotted as ANIX versus nadir reflectance instead of wavelength. For reasons of clarity, the wavelength range depicted is reduced to 675–1000 nm. The concrete slab has almost no variability for reflectance nor anisotropy. All vegetation objects, however, show a strong relationship between ANIX and nadir reflectance. Only in the sections where transmittance and reflectance are not highly correlated, a scattering in the data is introduced (compare Fig. 8). The highest anisotropy indices are observed in the low reflectance, that is, high absorbance range where multiple scattering is small. With increasing reflectance values, that is, with decreasing absorbance, multiple scattering becomes dominant and efficiently reduces anisotropy, demonstrating the soundness of the multiple scattering mechanisms outlined in the second section.

CONCLUSIONS

The results of the study indicate that basic physical mechanisms described accurately by Kimes (1983) for broad sensor bands are also applicable to hyperspectral data. BRDF effects in dense vegetation surfaces (i.e., no soil surface contributions) are caused by a combination of canopy structure and multiple scattering inside the canopy. The gap and backshadow effects underlying the impact of canopy geometry determine the distribution of shadow and light. Multiple scattered light fills in the shadow and decreases the contrast inside the canopy, thus reducing the extent of anisotropy.

Nadir-normalized BRDF data (i.e., anisotropy factors) reveal a high spectral variability and a discernible relationship with the nadir reflectance spectra. Low reflectance intensities are associated with high anisotropy, and high reflectance values are related to low anisotropy. This is due to multiple scattering effects inside a canopy which are a function of canopy absorbance, and therefore are inversely related to canopy reflectance. Hyperspectral BRDF data allow demonstrating the high continuity of this relationship over the spectrum, in our case between 450 nm and 1000 nm.

The ANIX data of grass, healthy and dying watercress demonstrate the high potential of hyperspectral BRDF data to characterize canopy architecture parameters. Since biophysical parameters are influenced by both canopy structure and reflectance/transmittance properties, there is hope that remotely sensed hyperspectral BRDF data improve the recognition and characterization of vegetation species including canopy structure parameters such as the leaf area index (LAI). Further developments of BRDF models and applications of hyperspectral BRDF data should therefore explicitly account for the spectral variability of the BRDF effect.

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