*Can. J. Remote Sensing*, Vol. 36, Suppl. 2, pp. S355–S364, 2010

# Anisotropic reflectance effects on spectral indices for estimating ecophysiological parameters using a portable goniometer system

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**Abstract.** Remote sensing studies are affected by the inherently anisotropic nature of reflectance from natural surfaces. The objective of this study was to investigate the effect of anisotropic reflectance on the 970 nm water band index (WBI) for *Pleurozium schreberi* moss from the Fluxnet Canada Western Peatland site in northern Alberta. A series of hyperspectral bidirectional reflectance measurements from the University of Lethbridge Goniometer System (ULGS-I) were assessed for their effect on a variety of WBI and NDVI spectral indices. These indices are often used to estimate ecophysiological parameters such as plant water content, pigment content, and leaf area and subsequently have the potential to contribute to estimates of ecosystem $CO_2$ flux across large regions. Estimates of the bidirectional reflectance distribution function (BRDF) from laboratory ULGS-I measurements of *P. schreberi* moss were made under controlled illumination conditions from which WBI and NDVI were computed to evaluate the variation in index magnitude by view direction. As view angle increased from nadir, WBI declined dramatically from 1.40 to 1.24, and NDVI values changed from 0.87 to 0.96. This finding increases our understanding of the effect of anisotropic reflectance on vegetation indices and enhances our ability to derive improved information from remote sensing data when these angular effects are prevalent for different surface targets.

**Résumé.** Les études de télédétection sont affectées par la nature anisotrope inhérente de la réflectance des surfaces naturelles. L'objectif de cette étude était d'étudier l'effet de la réflectance anisotrope sur l'indice WBI (« water band index ») à 970 nm de l'hypne de Schreber (*Pleurozium schreberi*) sur le site de la Station de flux des tourbières de l'ouest de Fluxnet-Canada située dans le nord de l'Alberta. Une série de mesures hyperspectrales de réflectance bidirectionnelle acquises à l'aide du système de goniomètre de l'Université de Lethbridge (ULGS-I) ont été évaluées pour leur effet sur divers indices spectraux WBI et NDVI. Ces indices sont souvent utilisés pour estimer les paramètres écophysiologiques tels que la teneur en eau des plantes, la teneur en pigments et la surface foliaire car ceux-ci peuvent ultimement contribuer aux estimations des flux de $CO_2$ de l'écosystème à travers de vastes régions. Des estimations de la fonction de distribution de la réflectance bidirectionnelle (FDRB) à partir de mesures de ULGS-I en laboratoire de l'hypne de Schreber (*P. schreberi*) ont été réalisées dans des conditions contrôlées d'éclairement à partir desquelles les indices WBI et NDVI ont été calculés pour évaluer la variation de la magnitude de l'indice selon la direction de visée. À mesure que l'angle de visée augmentait à partir du nadir, le WBI diminuait dramatiquement de 1,40 à 1,24 et les valeurs de NDVI changeaient de 0,87 à 0,96. Cette découverte améliore notre connaissance de l'effet de la réflectance anisotrope sur les indices de végétation et accroît notre capacité à dériver une meilleure information à partir des données de télédétection lorsque ces effets angulaires sont omniprésents pour différentes cibles de surface.
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## Introduction

Remote sensing offers one of the most efficient and cost-effective methods for assessing the dynamics of the Earth's surface over large areas. The utility of remote sensing to evaluate vegetation dynamics depends on the consistency of the data provided by the sensing system. A variety of useful spectral indices have been developed that use relatively stable spectral absorption and reflectance features for vegetated surfaces to ascertain temporal and spatial variation in plant health, density, and other biophysical parameters (Gitelson, 2004). Rouse et al. (1973) devised the normalized difference vegetation index (NDVI) to measure the magnitude of reflectance difference between chlorophyll

Received 15 October 2009. Accepted 21 May 2010. Published on the Web at http://pubservices.nrc-cnrc.ca/cjrs on 28 January 2011.

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absorption at red wavelengths (near 670 nm) and the strong reflectance feature in the near-infrared (NIR; 800 nm is commonly used). The success of this vegetation index (VI) has led to the development of many others and enhancements to NDVI in efforts to account for a variety of surface conditions and atmospheric effects (Huete, 1988; Clevers, 1989; Kaufman and Tanre, 1992; Qi et al., 1994) as reviewed by Bannari et al. (1995) and Chen (1996). Despite well-published shortcomings of VIs (e.g., Perry and Lautenschlager, 1984; Guyot et al., 1989; Spanner et al., 1990; Baret and Guyot 1991; Peddle et al., 2001), their simplicity, ease of computation, minimal input requirements, familiarity, and utility have resulted in sustained use for monitoring leaf area index (LAI), fraction of absorbed photosynthetic radiation (fAPAR), net primary productivity (NPP), and other important biophysical properties (Asrar et al., 1984; Sellers, 1985; Tucker et al., 1986; Chen and Cihlar, 1996).

VIs are affected by surface reflectance anisotropy, as evidenced by results obtained from different view and illumination angles. When completely measured for all angles, this is called the bidirectional reflectance distribution function (BRDF) (Nicodemus et al., 1977). Many previous studies have indicated that almost all natural surfaces are not perfectly diffuse; they reflect energy in different amounts at different angles (e.g., Syrén, 1994; Peddle et al., 2001). Although the remote sensing community has long recognized the anisotropic nature of surface reflectance, most remote sensing studies have focused on simple reflectance measurements without directly addressing the variation caused by view or illumination angle. Further, when angular effects have been considered, they have often been treated as variations that should be corrected, suppressed, or adjusted instead of using this additional information content to advantage.

Several studies have investigated the effect of view and illumination angle on a variety of vegetation indices. Most of these assessed VI variation with respect to view geometry using models of BRDF (Asrar et al., 1992; Wardley, 1984). Results varied from negligible to small effects (Wardley, 1984; Asrar et al., 1992) to dramatic change (Huemmrich and Goward, 1992). The range of these findings can be attributed partly to the domination of model-produced BRDF values that tend to simplify the BRDF, resulting in the lack of agreement between modelled and measured values (Solheim et al., 2000).

The BRDF is an important consideration in remote sensing studies of Earth surface features (Barnsley et al., 1994; Snyder, 1998). For example, the derivation of biophysical variables such as LAI, biomass, NPP, and fAPAR from remotely sensed data would be improved if accurate estimates of canopy BRDF were available (Combal et al., 2002; Sandmeier and Deering, 1999; Chen and Leblanc, 1997). Further, the development of canopy BRDF models has significantly contributed to an improved understanding of the angular interaction of solar energy with surface vegetation targets and the estimation of biophysical structural information (Li and Strahler, 1985; 1992; White et al., 2002; Peddle et al., 2004).

In this paper we assess the influence of reflectance anisotropy through BRDF estimates derived from a laboratory goniometer system for peatland moss targets. Anisotropic impacts on various VIs in this study were limited to what was observed at the surface from in situ measurements of reflectance. Increasing variation in the spectral region of the WBI has been demonstrated in other studies (see White et al., 1995) as well as seasonal effects but was not considered as part of this study. The rationale for this application is first established, followed by a description of sampling design, measurement protocols, and VIs derived. Significant results are then reported and discussed.

## Experimental design

### Application and rationale: carbon exchange, water content, and vegetation indices

Boreal ecosystems store large stocks of carbon (C) and are therefore important in climate change studies. In northern regions, mosses such as *Pleurozium* are abundant and play a key role in ecosystem function and atmospheric–biosphere C exchange (Gorham, 1991). According to the Intergovernmental Panel on Climate Change (IPCC, 2007), recent observations of global environmental changes such as elevated atmospheric $CO_2$ concentration, land use change, nitrogen deposition, and climate change are a concern for the functioning of terrestrial ecosystems. The IPCC (2007) reported that global atmospheric $CO_2$ concentration has risen 35% (from approximately 280 ppm to 379 ppm) over the last 200 years due largely to the burning of fossil fuels. Associated with the increased levels of greenhouse gases, global mean temperature has risen by 0.74 °C in the past century (IPCC, 2007).

Mosses are particularly sensitive to water content because they are nonvascular plants. The lack of root systems and leaf stomata can cause water content to vary widely over short time periods and can strongly influence moss $CO_2$ exchange. $CO_2$ supply is primarily influenced by large passive variations in moss water content (Clymo and Hayward, 1982). Studies of short-term dry-down response of moss have shown that net $CO_2$ uptake is reduced at both excessive and low water contents (Williams and Flanagan, 1998; Van Gaalen et al., 2007). Low water contents result in low net photosynthetic uptake because cell activity and metabolism decline (Silvola, 1990; Schipperges and Rydin, 1998; Proctor, 2000). At very high water contents, net $CO_2$ uptake is suppressed as $CO_2$ supply to chloroplasts is impeded because $CO_2$ diffuses slowly through water (Silvola, 1990).

The use of hyperspectral remote sensing shows potential for detecting subtle plant characteristics, including chlorophyll content (Gitelson et al., 1996), xanthophyll pigment contents (Gamon et al., 1997), leaf structure (Carter, 1991), and water content (Sims and Gamon, 2003), by evaluating changes in reflectance over specific wavelength regions. Given the tightly coupled relationship between $CO_2$ uptake and water content in mosses, spectral analysis of moss canopies is expected to yield reliable information on $CO_2$ flux by modelling moss water content (Van Gaalen et al., 2007).

Sims and Gamon (2003) defined a water index that showed a strong relationship to water content in various species. The water band index (WBI), the ratio of reflectance at 900 nm to that at 970 nm (Peñuelas et al., 1993; 1997), was found to detect changes in *Sphagnum* water content in controlled laboratory studies (Van Gaalen et al., 2007). Given the physiological link between water content and net photosynthetic rate, it may be possible to calculate moss net photosynthesis rate by estimating moss water content using the WBI.

Although simple reflectance measurements, and their derived indices, have dominated field and laboratory measurements in remote sensing science, it has long been understood that many factors can affect the viability of spectroradiometer-derived reflectance measurements (Milton, 1987; Milton and Goetz, 1997; Hatchell, 1999). These factors include anisotropic surface reflectance, the presence of multiple targets (spectral mixtures), and target structure and architecture (Milton, 1987; Huemmrich and Goward, 1997). The BRDF of many natural surfaces prevents simple characterizations of surface reflectance unless view angle and illumination remain constant for all samples over all spatial and temporal scales (Combal et al., 2002).

Studies have investigated the utility of hyperspectral remote sensing to estimate moss water content in the laboratory (Fernandes et al., 1996; Van Gaalen, 2005) and in the field (Bubier et al., 1997; Lovelock and Robinson, 2002; Houston, 2004). These studies did not investigate the effects of multi-angle viewing. Under controlled laboratory conditions, Van Gaalen et al. (2007) observed strong correlations between water content and WBI for *Sphagnum*. Strong correlations were also found between these variables for *Pleurozium* (Van Gaalen, 2005). When similar measurements were made in the field, very weak correlations were observed between WBI and water content for *Sphagnum* (Houston, 2004; Van Gaalen, 2005) and *Pleurozium* (Van Gaalen, 2005). The BRDF of the mosses may have been a significant complicating factor that had previously been controlled in laboratory experiments.

This paper investigates the effect of reflectance variability on WBI and NDVI measurements from *Pleurozium* moss at constant water content. A goal of this research was to help bridge controlled laboratory experiments for applications in the field. It also seeks to demonstrate the utility of a simple goniometer for the measurement of reflectance anisotropy to enhance our understanding of reflectance data.

## Data acquisition

### *Field data collection and sample preparation*

Moss samples were collected during August 2004 from a moderately rich fen (Vitt, 1994; Vitt et al., 1998) located in the Central Mixedwood Subregion of the Boreal Region of Alberta (Vitt et al., 1998; ANHIC, 2005). This western peatland flux station (54.95384°N, 112.46698°W) was a part of the Fluxnet Canada Research Network (FCRN) (Coursolle et al., 2006; Syed et al., 2006).

A sample of *Pleurozium schreberi* moss 60 cm × 30 cm × 20 cm (length × width × depth) was carefully cut and extracted from the peatland surface and then placed in a large plastic container and maintained in a growth chamber (I35L, Percival Scientific, Boone, Iowa). A combination of GROLUX and "cool white" fluorescent lighting provided 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ photosynthetic photon flux density (PPFD) at the moss surface for 16 $h \cdot day^{-1}$. Temperature was maintained at 22–24 °C during illumination and 18–20 °C during dark periods. A half litre of deionized water was applied using a mist sprayer at equal time intervals three times per week. Water-table depth from the moss surface was maintained at 15–18 cm to simulate the position of the moss surface above the water table in the field.

### *Goniometer measurements and vegetation indices*

A sequence of hyperspectral measurements were made of the *Pleurozium* target using the original University of Lethbridge Goniometer System (ULGS-I) as described in Coburn and Peddle (2006) and shown in **Figure 1**. The ULGS-I (**Figure 1**) records hyperspectral reflectance at predetermined zenith and azimuth angles. In standard operation, the ULGS-I controls spectral measurements over a full set of azimuths (0°–360°) and a restricted set of zenith angles (−60° to +60°).

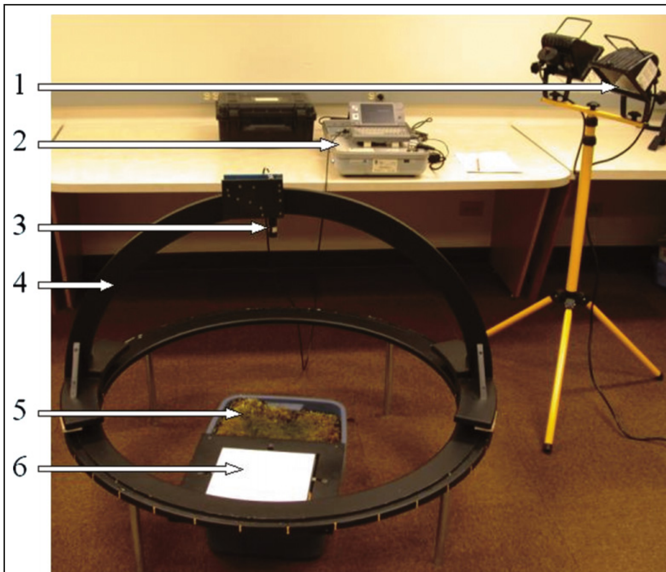


**Figure 1.** The University of Lethbridge Goniometer System (ULGS-I), showing the halogen light source (1), the ASD FR spectroradiometer (2) with foreoptic (3) attached to the goniometer arch (4), and two interchangeable targets of *Pleurozium* moss (5) and PTFE calibration panel (6). The field of view (FOV) on the moss surface at nadir was 10 cm. The surface condition of the moss was fairly uniform, with the variation being typical of what is observed in the field.

 

For this experiment, the ULGS-I was set to record hyperspectral reflectance measurements with 10° angular resolution in both the azimuth and zenith planes, generating 217 unique view angles (zenith, azimuth) of the moss surface. These values were then used to evaluate the anisotropic nature of the moss surface following the procedures outlined in Coburn and Peddle. The light source, a 500 W halogen lamp, remained in a fixed position illuminating the moss from 45° zenith and 150° azimuth and 1.5 m from the moss surface. The shadow cast by the arc was minimized by orienting the light source so that it was illuminating the target from an angle between measurement stations. The halogen light source was allowed a 30 min warm-up period prior to moss measurement (no target present) to ensure that illumination fluctuation due to lamp variation was minimized.

The total time for recording the reflectance values was 20 min, ensuring minimal change in moss water content or changes in moss surface temperature. A duplicate measurement was taken of the first azimuthal path at the end of the measurement cycle to ensure consistency of surface condition over the measurement cycle. The foreoptic for the ULGS-I is positioned 60 cm over the target at each measurement station. The instrument field of view (FOV) changes with every zenith position and becomes more elliptical for increasing view zeniths.

This sampling of the BRDF from a finite set of angles produces the bidirectional reflectance factor (BRF) of the surface. The BRF of a surface is the ratio of the BRDF from the target to the incident energy when measured under the same conditions (Nicodemus et al., 1977). As the BRF is the ratio of the two upwelling radiances measured under similar conditions, it is less sensitive to instrument and calibration error (Solheim et al., 2000).

The *Pleurozium* (water content = 10.9, calculated as fresh weight divided by dry weight) target in the original sampling container was placed underneath the goniometer, and spectral measurements were recorded with an Analytical Spectral Devices (ASD) FieldSpec full-range (FR) spectroradiometer (ASD Inc., Boulder, Colo.). The spectral resolution of the ASD FR at full-width half-maximum was approximately 3 nm between 350 and 1000 nm and 10–12 nm between 1000 and 2500 nm.

Measurements were automatically recorded as the average of 10 scans. Radiance data from the instrument were automatically output at 1 nm bandwidths consistent with data acquired in related vegetation index studies (Lovelock and Robinson, 2002; Stylinski et al., 2002; Sims and Gamon, 2003; Houston, 2004). Measurements were recorded at each zenith increment for a total of 13 radiance measurements per azimuth increment. Each azimuth set of 13 radiance measurements was preceded with dark current noise measurement (and subtraction) and a measurement of the calibration panel for calibration of radiance to reflectance. The incident energy was measured using a Spectralon reference panel, which is a diffuse reflective surface comprising ~99% reflective sintered polytetrafluoroethylene (PTFE) (Spectralon, Labsphere Inc., North Sutton, N.H.). Prior to acquiring radiance measurements, spectroradiometer sensitivity (optimization or integration time) was automatically adjusted to the maximum radiation intensity conditions with the sensor foreoptic positioned above the PTFE calibration surface at nadir. A complete estimation of the panel BRDF was also recorded at the time of measurement with reflectance values varying by less than 2% (Coburn and Peddle, 2006).

Using these reflectance values, WBI and NDVI were calculated for all viewing angles and plotted as surfaces to aid comparison between the VI values. WBI was calculated as the simple ratio (Birth and McVey, 1968; Jordan, 1969) at all zenith and azimuths for the wavelengths shown in the following equation (Peñuelas et al., 1993; 1997):

$$\mathrm{WBI} = \frac{R_{900}}{R_{970}} \tag{1}$$

where $R$ is reflectance, and the subscripts refer to the wavelength in nanometres (nm).

Immediately following the reflectance measurements, moss water content was obtained by collecting and weighing three clippings from the moss surface. Next, the clippings were dried at 60 °C for 24 h, and the dry weights were then measured, allowing for calculation of water content in terms of fresh weight divided by dry weight.

NDVI was calculated from the red and NIR wavelengths (in nm) after Rouse et al. (1973) using the following equation:

$$\mathrm{NDVI} = \frac{R_{800} - R_{670}}{R_{800} + R_{670}} \tag{2}$$

## Results

As moss is a nonvascular plant, changes in water content (wilting) during the experiment were of concern because changes in the water content during the measurement cycle would appear as variation in reflectance values not accounted for by view or illumination geometry. Although the surface temperature was not monitored during the experiment, additional reflectance measurements were recorded to ensure that surface water content remained similar during the measurement cycle. Start and finish measurements of surface reflectance from the first azimuthal path were compared and revealed an average difference of 0.8% over the measurement cycle, with a standard deviation of 0.042. This result indicates that the surface was consistent during the measurement time period.

Measurements of bidirectional reflectance using an ASD FR FieldSpec spectroradiometer mounted on the ULGS-I goniometer showed variability in WBI depending on view angle (**Table 1**; **Figures 2** and **3**). In **Table 1**, the first three columns describe values of reflectance at 900 nm, reflectance at 970 nm, and WBI acquired from all hemispherical measurements except one angle (azimuth = 180°, zenith = 20°)

 

**Table 1.** Reflectance and WBI values of *Pleurozium* measured from a detailed series of zenith and azimuth angles using an ASD spectroradiometer attached to the ULGS-I goniometer.

| | $R_{900}$ | $R_{970}$ | WBI | WBI n | WBI nn | WBI 60 | WBI 40 |
|---|---|---|---|---|---|---|---|
| Mean | 0.58 | 0.43 | 1.35 | 1.39 | 1.35 | 1.32 | 1.35 |
| SD | 0.064 | 0.054 | 0.040 | 0.031 | 0.039 | 0.027 | 0.021 |
| SE | 0.004 | 0.003 | 0.003 | 0.007 | 0.003 | 0.006 | 0.005 |
| *N* | 246 | 246 | 246 | 19 | 226 | 19 | 19 |
| Min. | 0.23 | 0.17 | 1.23 | 1.29 | 1.23 | 1.26 | 1.29 |
| Max. | 0.85 | 0.65 | 1.46 | 1.43 | 1.46 | 1.36 | 1.40 |
| Range | 0.63 | 0.48 | 0.23 | 0.14 | 0.23 | 0.10 | 0.11 |
| Estimated[a] | | | 12.9 (1.2) | 13.9 (0.9) | 12.8 (1.2) | 11.8 (0.8) | 12.8 (0.6) |

**Note:** $R_{900}$ and $R_{970}$, reflectance at 900 and 970 nm, respectively; WBI, water band index; WBI n, WBI at nadir; WBI nn, WBI at all angles but nadir; WBI 60, WBI at 60° from zenith; WBI 40, WBI at 40° from zenith.

[a]Values are given as means with standard deviation in parentheses.

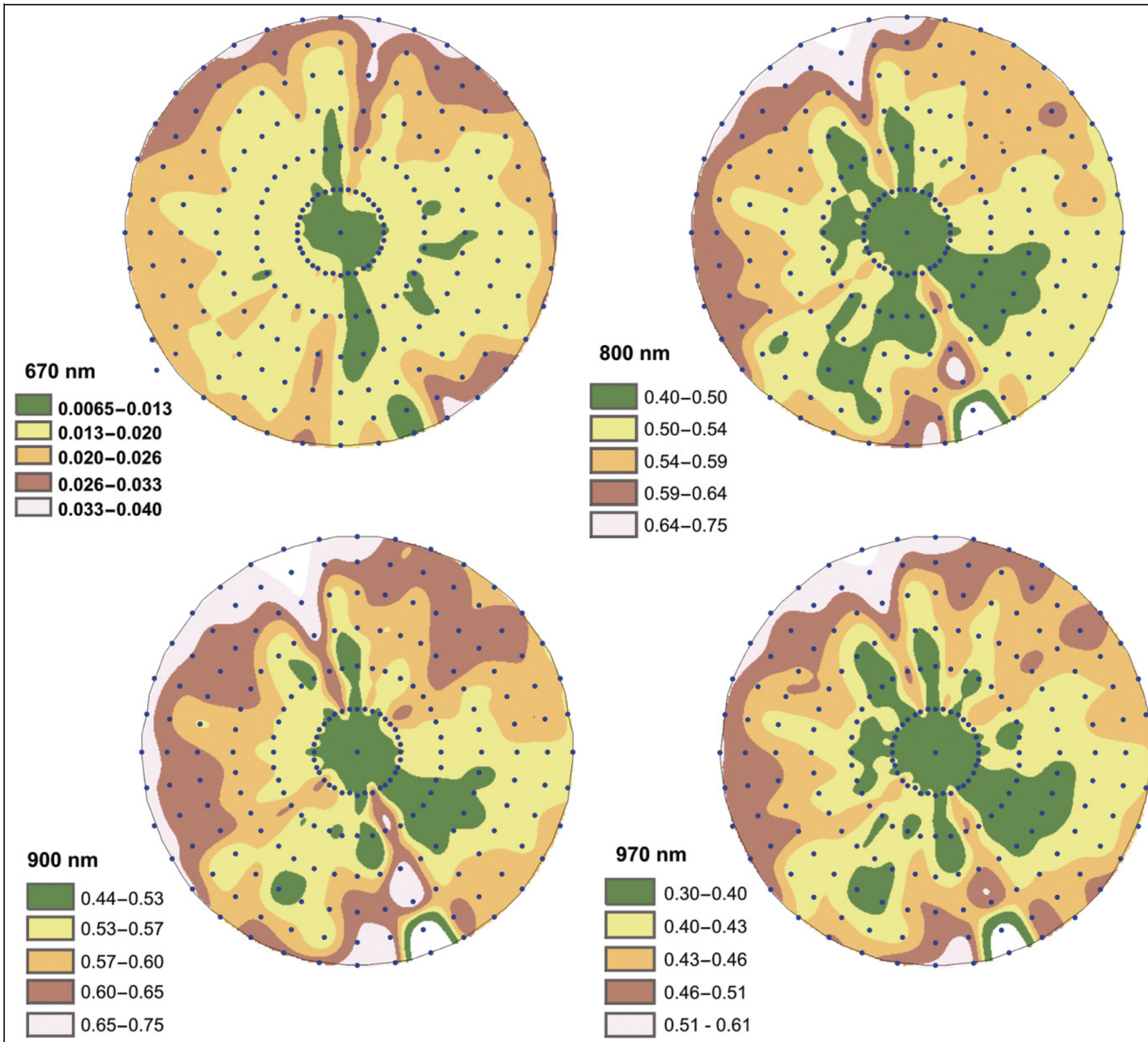


**Figure 2.** BRF surfaces created for each waveband used in deriving the vegetation indices used. In each plot, the blue points that form a circle show the various view azimuth angles of spectral measurements (principal plane oriented vertical on the page, with illumination from the bottom of the figure). The distance of each circle from the centre corresponds to the view zenith angle, ranging from 0° at centre (nadir) to 60° at the outermost circle.

due a problematic file. The remaining columns describe WBI values recorded from zenith only (WBI n), all prescribed angles excluding zenith recordings (WBI nn), all values recorded at 60° from zenith only (WBI 60), and all values recorded at 40° from zenith only (WBI 40). In the bottom row labelled "estimated," *Pleurozium* water content was estimated using the linear regression equation: water content = (WBI – 0.916)/0.0339, derived from dry-down experiments with *P. schreberi* from Van Gaalen (2005). These estimated water contents are expressed as mean values with standard deviations in parentheses. Actual mean water content (fresh weight divided by dry weight) measured from three clippings of the moss was found to be 10.9, with a standard error of the mean of 0.408.

Values in **Table 1** show that WBI was lower as the viewing angle increased from nadir. At nadir, mean WBI was 1.39. Increasing the viewing angle to 40° yielded a mean WBI of 1.35. A further increase in viewing angle to 60° resulted in a further decrease in mean WBI to 1.32. The three mean values of WBI n, WBI 40, and WBI 60 were all statistically significantly different from each other based on one-way analysis of variance ($F = 32.3$, df = 54, $p < 0.05$) and subsequent Tukey tests ($T = 0.0208$, $a = 3$, $v = 54$, $p < 0.05$). The ANOVA was preceded by a test for homogeneity of variance ($F_{max} = 2.07$, df = 18, $p < 0.05$).

The BRF plots for each of the wavebands used to generate the WBI (900 and 970 nm) and NDVI (670 and 800 nm) are displayed in **Figure 2**. The illumination angle has been rotated in all BRF plots so that the illumination principal plane is oriented vertically in the figure. The pattern of illumination variation differs for each individual waveband but follows a primarily symmetrical pattern around the principal plane. **Figure 3** displays the results of the two vegetation indices.

**Figure 4** is a graph of the data shown in **Figure 3** and provides additional insight into the nature of the VIs calculated. It is a linear plot of index values versus zenith angle for all recorded azimuths in sequence from the start azimuth of 0°–180° and progressing clockwise. This figure shows the periodic nature of the BRF with each measurement station over the arch from +60° to −60° (labelled as A in **Figure 4**) displaying lower values for the calculated index at the lower view angles.

**Figure 2** shows the angular distribution of reflectance values for the set of view zenith and azimuth angles measured. When viewed as a three-dimensional interpolated surface (not shown) from the $R_{900}$ and $R_{970}$ data, the shape of the multiview angle point data resembled an upright bowl. That is, higher zenith view angles generally yielded higher NIR reflectance values. The surface diagram of WBI exhibited a pattern resembling the opposite, namely an inverted bowl shape (**Figure 3**). This resulted from a difference in reflectance magnitude between $R_{900}$ and $R_{970}$ while approximately equal changes occurred in reflectance for both $R_{900}$ and $R_{970}$. As a result, $R_{970}$ was disproportionately elevated relative to $R_{900}$ as the zenith angle was increased. For example, from zenith to 60° from zenith, the absolute increase in reflectance was the same (10%) for these two bandwidths, but the relative increase in reflectance was greater for $R_{970}$ (25%) than for $R_{900}$ (18%).

The calculated WBI value was approximately 1.4 when viewed from zenith and 1.46 (the maximum observed value) when viewed from 160° azimuth and 30° zenith. In general, the farther the view angle was from zenith, the lower the

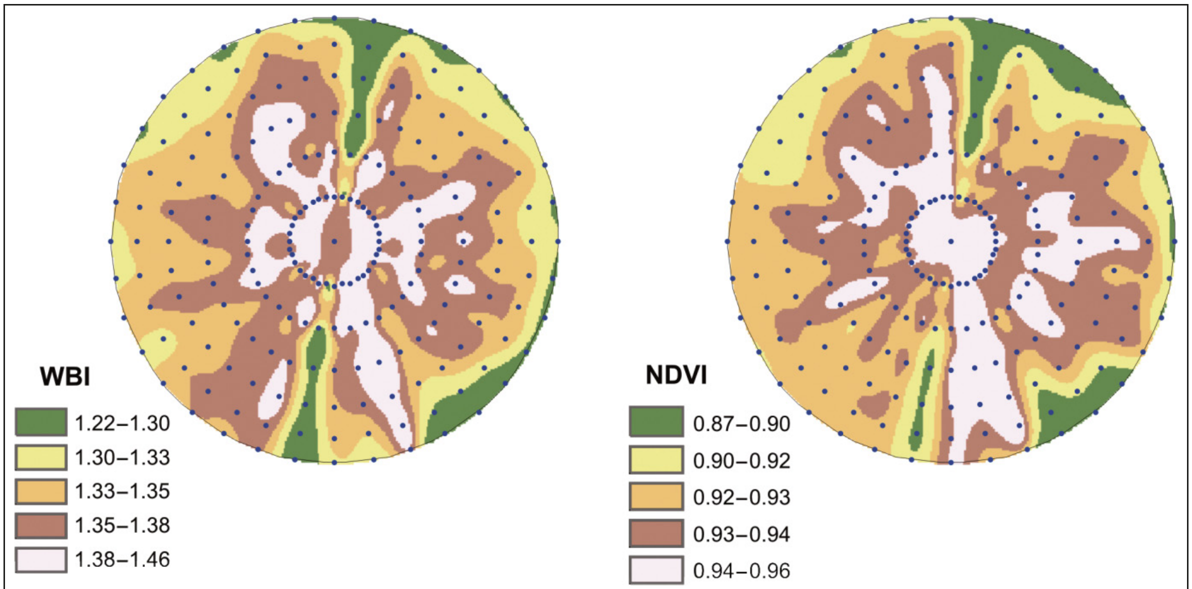


**Figure 3.** Vegetation indices computed from BRF surfaces. In each plot, the blue points that form a circle show the various view azimuth angles of spectral measurements used to derive each vegetation index (principal plane oriented vertical on the page). The distance of each circle from the centre corresponds to the view zenith angle, ranging from 0° at centre (nadir) to 60° at the outermost circle.

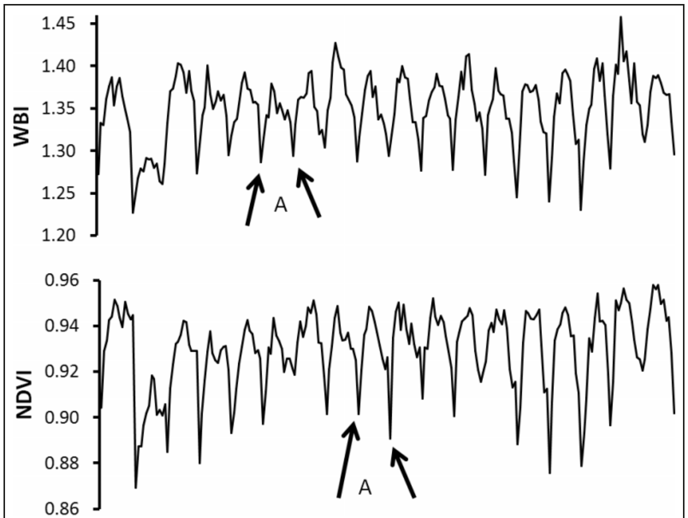


**Figure 4.** WBI and NDVI variation with changing view azimuth and zenith. The area indicated by the arrows (A) shows a single azimuth measurement path (from −60° to +60° zenith) along the goniometer arch.

measured WBI value. The lowest WBI value (1.23) occurred when viewed from an azimuth of 150° and a zenith of 60°. Water content was estimated for each WBI value (second *y* axis) using the laboratory dry-down experiment regression equation: estimated water content = (WBI – 0.916)/0.0339 derived from dry-down experiments with *P. schreberi* from Van Gaalen (2005).

The highest and lowest WBI values of 1.23 and 1.46 modelled water contents of 9.3 and 16.0 (fresh weight divided by dry weight), respectively. The measured water content of *Pleurozium* during goniometer measurements was 10.9, which yields a WBI value of ~1.3 based on the same regression equation (**Figure 5**). The mean WBI values from the goniometer were higher than the expected WBI value. Only the mean of the WBI values measured from 60° zenith had a standard deviation range that overlapped with the expected WBI (**Table 1**). **Figure 5** shows the graph of the first measurement location azimuth (0°–180°) and the estimated water contents, with the measured water content shown as a broken line.

## Discussion

The results of this research demonstrate the range of potential variability in surface reflectance caused by anisotropic reflectance of a moss surface. Measurements made using goniometer systems are subject to a changing FOV with increasing zenith view angles from nadir. This measurement method is consistent with measurements made from all remote sensing systems. Over the zenith range of this instrument, the FOV would approximately double at 60° in the azimuth direction (to approximately 18 cm). The net effect of this FOV increase is an enlargement of the overall sampling footprint to approximately 26 cm for a single measurement. The combination of all

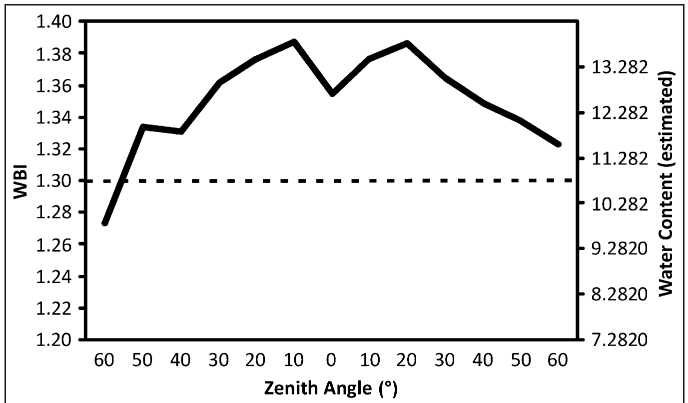


**Figure 5.** Graph of the WBI values and estimated water contents for a single measurement station (0°–180° azimuth) for all zenith angles. The measured water content is shown as the broken line. This figure demonstrates the consistent overestimation of WBI values.

view ellipses would produce a variation in spatial sampling density with the nadir remaining constant but with additions in sample area for off-nadir positions. This produces a spatial discontinuity in the sampling effort and may account for some of the lack of symmetry observed in this study. No corrections are applied to these measurements because the measurements are made with the same principles as those for imaging remote sensing systems.

Given the range of variability that is possible, this research has demonstrated that large variations in WBI (1.24–1.40) and NDVI (0.86–0.95) were possible for a single location on the moss surface at a static water content. If converted to carbon flux values using the relationships of WBI to water content and subsequently water content to $CO_2$ flux (Williams and Flanagan, 1996; 1998; Van Gaalen et al., 2007), the results could be subject to large errors depending on the positions of the sun and sensor. The range of predicted water contents from these measurements would represent a relatively saturated moss condition with significant variation in net photosynthetic rate. The low end of the estimated water content (9.2) would represent a less than optimal water content and as a result an inhibition to net photosynthetic rate, and the upper estimated water content value (16) that was outside of the range of measured values for net photosynthetic rate and could not be predicted using the equations presented by Williams and Flanagan (1998).

This result demonstrates the large and significant difference between field and laboratory spectral measurements. Results of field investigations are subject to significant, but measureable variance. This result suggests that variations in sun angle, even while maintaining the view angle at zenith, will result in significant variation in measured reflectance. Therefore, the configuration of sensor and illumination angle has implications for the interpretation of this index specifically and other spectral indices in general. This study also demonstrates that the inherent complexity of a measured BRF as opposed to the relatively smooth renderings produced from models can lead to measurement variation regardless of the style of vegetation index used. Simple ratios (e.g., WBI) and normalized ratios (e.g., NDVI) and their variants would be subject to these types of measurement uncertainty without the measurement of the BRF of the surface.

Although laboratory evidence has demonstrated significant relationships between WBI, water content, and, by extension, $CO_2$ flux, without accounting for angular relationships these measurements would be questionable if scaled from laboratory experiments at the centimetre scale to satellite images at the metre or kilometre scale.

## Conclusion

By measuring the anisotropic reflectance effects of a plant canopy, the recorded BRF can be exploited as a rich source of remotely sensed data. The additional information provided by the angular dimension is important for both target identification and information extraction. Information on the anisotropic nature of natural surfaces will provide additional information on reflectance variability and may assist in our understanding of satellite sensors with multi-angle viewing capabilities such as the System pour l'Observation de la Terre (SPOT 2004) and the Moderate Resolution Imaging Spectroradiometer (MODIS) (Schaaf et al., 2002; Vanacker et al., 2005).

Laboratory bidirectional reflectance measurements using a goniometer enabled study of the susceptibility of vegetation indices to variable configurations of illumination and sensor geometry. It was evident that bidirectional reflectance effects must be considered when making repeatable reflectance measurements of vegetation canopies.

Advancing knowledge of how dynamic angular reflectance interacts with vegetation can enable improvements to existing processes that seek to acquire physiological information. This process requires determining the relationships between spectral responses of a feature in various conditions relative to sensor angle. Thus, this would yield a ''BRF Spectral Library'' that defines these relationships for use in feature-extraction postprocessing of remote sensing data. For example, known BRF characteristics of wet moss versus dry moss (and intermediate water contents) can improve discrimination of moss water content, thereby enabling calculation of net photosynthesis rates using parameter-driven models of moss physiology (Williams and Flanagan, 1998). In turn, carbon flux values derived from remote sensing data can be used to efficiently quantify the contribution of mosses to net ecosystem exchange and to investigate how environmental changes such as global warming interact with carbon pools and fluxes.

## Acknowledgements

This research was part of the Fluxnet Canada Research Network and was supported by grants from the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS), BIOCAP Canada, and the University of Lethbridge.

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