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An Anisotropic Flat Index (AFX) to derive BRDF archetypes from MODIS

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ABSTRACT

Spectral vegetation indices can be generalized as a function of surface reflectance with respect to wavelength. However, there is significant information on vegetation structure embedded in the anisotropic effects of the target. In this study, we describe and characterize a new vegetation index, the Anisotropic Flat Index (AFX) that captures this anisotropic scattering information and can be derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) bidirectional reflectance distribution function (BRDF) product suite (MOD43A1). The AFX is created by normalization of net scattering magnitude (obtained from volumetric and geometric-optical scattering) with the isotropic scattering. The AFX summarizes the variability of basic dome-bowl anisotropic reflectance patterns of the terrestrial surface. A classification scheme for BRDF typology is created based on AFX archetypes that capture characteristic BRDF shape types. This study fully characterizes AFX in a number of steps. First, sensitivity to random noise and observation geometries is explored by comparing the AFX with other variables derived from field measurements that comprehensively sample the viewing hemisphere. Second, AFX is compared with normalized difference vegetation index (NDVI) values using field measurements from many ground campaigns, as well as global MODIS observations from EOS Land Validation Core Sites (LVCS). Third, a BRDF typology is developed by classification of an a priori database of BRDF archetypes from field measurements, and from MODIS observations that cover the full range of vegetation types from grasslands to closed forest (MCD43A). Fourth, the response of AFX to the parameter variability of canopy architectures and background optical properties for three vegetation types with discontinuous woody canopies is investigated through the use of a 5-Scale BRDF model simulation. Finally, global BRDF archetypes are mapped and discussed through the use of a global high-quality MODIS BRDF/albedo gap filled product (MCD43GF). The results show that the AFX summarizes BRDF archetypes and provides additional information on vegetation structure and other anisotropic reflectance characteristics of the land surface.

1. Introduction

Methods that collapse spectral and (or) directional scattering data from remote sensing into simplified index formulations are widely accepted for retrieval of land surface information. Such vegetation indices have proven valuable in many fields of terrestrial science applications that aim to monitor and characterize the Earth's vegetation cover. Conventional spectral vegetation indices can be derived from surface reflectance using specific wavelengths (Huete, 1988; Myneni, Hall, Sellers, & Marshak, 1995), and have been widely used as indirect measures of various biophysical and biochemical variables, including leaf area index (LAI) (Boegh et al., 2002; Chen & Cihlar, 1996; Haboudane, Miller, Pattey, Zarco-Tejada, & Strachan, 2004), the fraction of photosynthetically active radiation absorbed by vegetation (FPAR) (Cohen, Maiersperger, Gower, & Turner, 2003; Di Bella, Paruelo, Becerra, Bacour, & Baret, 2004; Myneni, Ramakrishna, Nemani, & Running, 1997) and vegetation water content (Ceccato, Tarantola, Jacquemoud, Gregoire, & Flasse, 2001; Tucker, 1980). With conventional spectral vegetation indices, the anisotropic effects of the target are usually treated as perturbing factors considered to be a source of uncertainty in quantitative assessment. Therefore, many methods for deriving traditional spectral vegetation indices usually utilize remote sensing observations near or normalized to nadir, and the angular variations of the radiometric signal are frequently removed through an angular normalization technique (Leroy & Roujean, 1994; Lucht, Schaaf, & Strahler, 2000). Global land cover maps have been developed mainly by using multispectral nadir signals and the change in those multispectral signals through an annual cycle, including data from sensors such as the Advanced Very High Resolution Radiometer (AVHRR, Loveland et al., 2000), MODIS (Friedl et al., 2002, 2010), SPOT-Vegetation (Bartrlev, Belward, Erchov, & Lsaev, 2003) and the Medium Resolution Imaging Spectrometer (MERIS, Bicheron et al., 2008). On the other

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hand, both measurement and modeling have shown that multi-angular remote sensing can enhance the retrieval of global land surface properties, including albedo (Bicheron & Leroy, 2000; Martonchik, Pinty, & Verstraete, 2002; Schaaf et al., 2002), land covers (DE Colstoun & Walthall, 2006; Galvao, Roberts, Formaggio, Numata, & Breunig, 2009; Heiskanen & Kivinen, 2008; Jiao & Li, 2012; Jiao et al., 2011) and other key surface biophysical quantities for ecological and biological studies (Asner, 2000; Chen, Liu, Leblanc, Lacaze, & Roujean, 2003; Chopping et al., 2008; Gao, Schaaf, Strahler, Jin, & Li, 2003; Wang et al., 2011).

The anisotropic effects of the land surface on spectral reflectance can be captured by angular vegetation indices (thus BRDF shape indicators). Angular vegetation indices have been derived from the model parameters of kernel-driven linear BRDF models (Gao et al., 2003; Roujean & Lacaze, 2002). An anisotropic factor (ANIF), an anisotropic index (ANIX) and the normalized difference between red and near infrared (NIR) ANIX (NDAX) (Sandmeier & Deering, 1999; Sandmeier, Muller, Hosgood, & Andreoli, 1998) have all been suggested as ways to explore the physical mechanism of hyper-spectral BRDF effects and their relationship to land cover types. The hot-dark spot index (HDS) and the normalized difference between hotspot and dark spot (NDHD) (Chen, Menges, & Leblanc, 2005; Chen et al., 2003; Lacaze et al., 2002; Leblanc et al., 2005) are sensitive to the angular reflectance of photosynthetically active radiation (PAR) from sunlit and shaded leaves, and have been used to derive measures of foliage clumping. Roujean and Lacaze (2002) used model parameters derived from satellite retrievals with a kernel-driven linear BRDF model for global mapping of vegetation parameters. Gao et al. (2003) used similar model parameters and suggested a Structural Scattering Index (SSI). The HDS has also been used in combination with the NDVI to generate the normalized hotspot-signature vegetation index (NHVI) for the estimation of leaf area index (Hasegawa, Matsuyama, Tsuzuki, & Sweda, 2010).

These angular vegetation indices have been applied in various studies that seek to retrieve additional information to enhance assessment of land cover/dynamics (D'Entremont, Schaaf, Lucht, & Strahler, 1999; Gao et al., 2003; Jiao et al., 2011; Roujean & Lacaze, 2002; Sandmeier & Deering, 1999; Su, Chopping, Rango, Martonchik, & Peters, 2007) and canopy structures (e.g., canopy density, foliage clumping factor) (Chen et al., 2003, 2005; Gao et al., 2003; Hill, Averill, Jiao, Schaaf, & Armston, 2008, Hill et al., 2011; Lacaze, Chen, Roujean, & Leblanc, 2002; Leblanc & Chen, 2001, Leblanc et al., 2005; Nolin, 2004). However, to date, angular indices have not been used to derive a standard classification of BRDF typology, i.e., to generalize BRDF archetypes from various realistic BRDF shapes into a few BRDF-based classes for potential ecological applications and thus building on the early work of Strugnell and Lucht (2001) and Strugnell, Lucht, and Schaaf (2001).

The early efforts by Strugnell and Lucht (2001) and Strugnell et al. (2001) used 68 field multi-angle measurements (all measurements have been utilized in this study as well) to derive 25 so-called BRDF-based classes by cross walking with ecological land cover types. A major challenge for this method results from more complex heterogeneous environments within a surface type that tend to generate a high within-class BRDF variation (e.g., areas with heterogeneous patchiness resulting from forest fires or deforestation, and areas with a wide range of discontinuous tree canopy cover fractions and spatial arrangements). With 13 years of MODIS BRDF model parameter data accumulated, various efforts have been made to apply these model parameter data to estimates of biophysical parameters (e.g., Landsat albedo by Shuai, Masek, Gao, & Schaaf, 2011). A major challenge in directly using the entire per-pixel MODIS BRDF parameter data results in conjunction with data from other sensors is the pixel scale mismatch between different spatial resolution images. Román et al. (2013) pointed out that spatial scale errors can produce relatively high retrieval uncertainties in validating albedo measurements acquired from space. At present, cross walking a land cover map with BRDF shapes remains a desired approach despite its attendant classification accuracy and generalization issues. Therefore, developing a framework to extract the basic BRDF shapes from the multiyear MODIS model parameter data remains an important challenge. It is particularly important to determine the sensitivity of these basic BRDF shapes to canopy architecture associations and background optical properties, especially for discontinuous multilayer vegetation canopies. Additionally, these basic BRDF shapes could be used as a priori knowledge in estimation of biophysical parameters for certain ecological applications.

This study provides a major advance on the work of Strugnell and Lucht (2001) and Strugnell et al. (2001) by combining MODIS BRDF model parameter data into a more generic Anisotropic Flat Index (AFX) based on kernel-driven linear BRDF model theory. The work by Strugnell et al. (2001) was a quite rudimentary attempt to develop an a priori BRDF database, and is actually no longer used by the MODIS algorithm which has access to considerable NASA processing power and the luxury of using the most recent BRDF retrieval for that pixel directly. But for applications which do not have access to such resource, a generalized anisotropy flat index provides some ancillary information. The study a) explores the general characteristics of AFX in relation to the anisotropic reflectance patterns of land surface; b) investigates the uncertainty and sensitivity of AFX to observation geometries and random noise; c) analyzes the new information provided by the AFX in comparison with a traditional spectral vegetation index for MODIS observations and explores its response to canopy architectures and background optical properties for three vegetation types with discontinuous woody canopies through use of a 5-Scale BRDF model simulation; d) generates an a priori database of BRDF archetypes based on AFX; and e) maps BRDF archetypes for the globe and initially compares these to MODIS International Geosphere-Biosphere Program (IGBP) land cover classes.

2. Methods

2.1. Theoretical basis

2.1.1. Ross–Li model

The Ross–Li model is a further development of kernel-driven Roujean BRDF model (Roujean, Leroy, & Deschamps, 1992) that is linear combination of three basic scattering components: isotropic scattering, volume scattering and geometric-optical surface scattering. This model adopted a general form (Lucht et al., 2000; Roujean et al., 1992; Wanner, Li, & Strahler, 1995):

$$R(\theta_v, \theta_s, \Delta\phi\lambda) = f_{\mathrm{iso}}(\lambda) + f_{vol}(\lambda)K_{\mathrm{vol}}(\theta_v, \theta_s, \Delta\phi) + f_{\mathrm{geo}}(\lambda)K_{\mathrm{geo}}(\theta_v, \theta_s, \Delta\phi) \quad (1)$$

where $f_{\mathrm{iso}}(\lambda)$, $f_{vol}(\lambda)$ and $f_{\mathrm{geo}}(\lambda)$ are the spectrally dependent model parameters. $K_{\mathrm{vol}}(\theta_v,\theta_s,\Delta\phi)$ and $K_{\mathrm{geo}}(\theta_v,\theta_s,\Delta\phi)$ are kernel functions of view zenith θ_v, illumination zenith θ_s and relative azimuth $\Delta\phi$, providing shapes for volumetric scattering and geometric-optical scattering BRDFs; $f_{\mathrm{iso}}(\lambda)$ is a spectral constant for isotropic scattering that determines optical properties in relation to reflectance and transmittance of vegetation foliage and background; $f_{vol}(\lambda)$ and $f_{\mathrm{geo}}(\lambda)$ are spectral constants that weight the two BRDFs; $R(\theta_v,\theta_s,\Delta\phi\lambda)$ is bidirectional reflectance distribution function in waveband λ.

The Ross–Li model was originally designed to include a series of kernels for various land cover types in MODIS (Wanner et al., 1995). Volumetric scattering kernels include RossThick kernel for a big leaf area index (LAI $\gg$ 1) and RossThin kernel for a small LAI (LAI $\ll$ 1), which were originally developed by (Roujean et al., 1992), based on an assumption of a single-scattering approximation of the radiative transfer (RT) theory by Ross (1981). These two volumetric kernels take the reciprocal form, i.e., the sunlit component is simply assumed to vary as reciprocal of cosine of view zenith (Roujean et al., 1992; Wanner et al., 1995). Geometric-optical kernels include the LiSparse, the LiDense (Wanner et al., 1995) kernels for discrete clumping vegetation crown with low and high density, and the LiTransit (Gao, Li, Strahler, & Schaaf, 2000; Li, Gao, Chen, & Strahler, 1999) kernel for