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Mapping forest background reflectivity over North America with Multi-angle Imaging SpectroRadiometer (MISR) data

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ABSTRACT

The spatial and temporal patterns of the forest background optical properties are critically important in retrieving the biophysical parameters of the forest canopy (overstory) and in ecosystem modeling. In this paper we carry out background reflectivity mapping over conterminous United States, Canada, Mexico, and the Caribbean land mass using Multi-angle Imaging SpectroRadiometer (MISR) data at 1.1 km resolution. The refined methodology uses the nadir and 45° forward directions of the MISR camera images. The background reflectivity is shown to vary between coniferous and deciduous stands, particularly in the near-infrared band, and with the overall amount of overstory vegetation. The largest seasonal differences were observed over a boreal region. The main drawback is a high amount of missing MISR data due to the presence of clouds and other atmospheric effects. The paper also contains a demonstration of the effect on LAI estimates when the dynamic background reflectivity information is inserted into a global LAI algorithm. Multi-angular remote sensing is thus shown to enable us to effectively map yet another forest structure parameter over large areas, which was not possible using mono-angle data.

1. Introduction

Quantitative description of vegetation structure has been identified as one of the key requirements for major improvement in modeling the terrestrial carbon cycle and global biosphere (Turner et al., 2004). Vegetation canopy structure and its energy absorption capacity can be described by leaf area index (LAI), defined as half the total developed area of green leaves per unit ground horizontal area (Chen & Black, 1992) and by the Fraction of Photosyntetically Active Radiation (FAPAR) absorbed by the leaves. It was noted that for models of climate, hydrology, and ecology it is probable that only the LAI, FAPAR, and information about the forest floor albedo have to be estimated spatially (Diner et al., 2005). Other parameters can be derived from LAI or taken from the literature (Manninen & Stenberg, 2009).

While retrieving the information about forest vegetation structure such as LAI, it is the spectral signal from the forest canopy (overstory, see Fig. 1) that is the target in many remote sensing (RS) applications, and not the background. However, the sensor receives a signal from both the target and the background (Olofsson & Eklundh, 2007; Peltoniemi et al., 2005a). By the term forest background, we refer to all the materials below the forest canopy such as understory, leaf litter, grass, lichen, moss, rock, soil, snow, or their mixtures (Fig. 1).The stand is thus conceptually divided into tree canopy and background material + soil (Chopping et al., 2006).

The lack of spatial information about forest background and its importance has recently gained increased attention (e.g. Eriksson et al., 2006; Kuusk et al., 2004; Rautiainen, 2005). Particularly within relatively open forest canopies, understory vegetation, its contrasting greenness and senescence can be quite important to relationships between vegetation indices (VI) and overstory LAI (Pocewicz et al., 2007). Further, Garrigues et al. (2008) noted in their validation and intercomparison of global LAI products that the forest understory LAI is not systematically taken into account in ground LAI measurements. This can result in substantial differences with the satellite LAI product derived from the vertical integration of the radiometric signal within the canopy (Abuelgasim et al., 2006; Chen et al., 1997; Iiames et al., 2008; Wang et al., 2004). It is equally important to take the understory vegetation into account when measuring FAPAR, particularly in open canopies (Olofsson & Eklundh, 2007).

Driven by these calls, few efforts were carried out at collecting various understory components and/or creating limited spectral banks (Lang et al., 2002; Miller et al., 1997; Peltoniemi et al., 2005a,b; Rautiainen et al., 2007; Rees et al., 2004). Monitoring the environment at a continental or global scale over periods of multiple years requires access to continuous fields of geophysical quantities, and satellite RS is the only technology currently able to provide consistent data at these scales (Pinty et al., 2008). The information conveyed about canopy structure is small in the case of a mono-angle instrument, whose footprint does not spatially resolve individual scene elements

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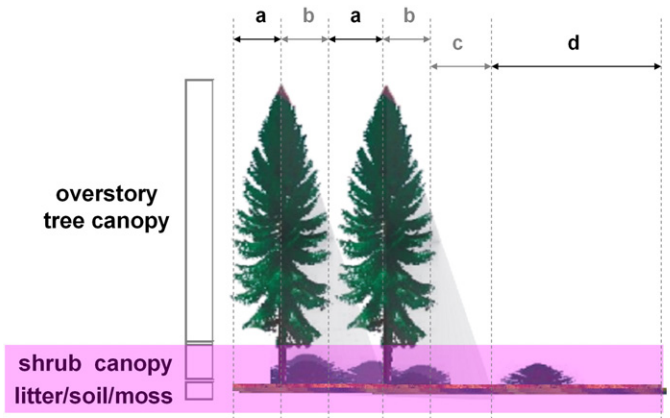

Fig. 1. Conceptual scheme of a forest stand. In vertical dimension the forest consists of overstory tree canopy; everything below (in purple) is considered to be the forest background. In horizontal dimension, the total reflectance of the stand is the sum of (a) sunlit tree, (b) shaded tree, (c) shaded ground, and (d) sunlit ground fractions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Fig. 1). Therefore specifically in reference to LAI, a wide range of natural variation in LAI and soil or understory reflectance can result in the same value of the remotely sensed signal. This results in a high uncertainty in retrieved values of LAI (Hu et al., 2003). Before the era of simultaneously acquired multi-angle RS data by sensors such as MISR (Diner et al., 1998) or POLDER (Leroy & Lifermann, 2000) really started, Gemmell (2000) summarized that in the large majority of situations, the background spectral characteristics cannot be effectively obtained from the mono-angle RS data.

The use of multi-angle RS for characterizing surface properties represents a new paradigm in optical RS application (Nolin, 2004), where the variation in reflectance with view angle is considered a source of new information rather than noise. Multi-angle RS enables us now to describe surface properties by means that are not possible using mono-angle data (for a comprehensive review of the progress, see Chopping, 2008).

In this paper, we intend a) to document an improved retrieval strategy for the background reflectivity retrieval using geometrical optical modeling theory with the 4-Scale model and MISR data from the initial study published by Canisius and Chen (2007); b) to examine the optical properties and seasonal changes of the forest background over conterminous United States, Canada, Mexico and the Caribbean land mass over the year 2007; and c) to present on the example of the existing global LAI algorithms of Deng et al. (2006) a preliminary analysis of the effects of using the new background information dataset to correct the forest LAI estimates.

The improved strategy has been previously field-tested with multi-angle airborne Compact Airborne Spectrographic Imager (CASI) data (Pisek et al., 2009). The current paper presents, for the first time, a forest background dataset retrieved from MISR data at a continental scale and the implications for global LAI mapping.

2. Materials and methods

2.1. Background reflectivity algorithm

Since radiance is additive, the total spectral reflectance of a pixel (R) can be expressed as a linear combination of the contributions from the scene components (Bacour & Bréon, 2005; Chen et al., 2000; Chopping et al., 2008; Li & Strahler, 1985):

$$R = R_T \cdot k_T + R_G \cdot k_G + R_{ZT} \cdot k_{ZT} + R_{ZG} \cdot k_{ZG} \tag{1}$$

where R_T, R_G, R_{ZT}, and R_{ZG} are the reflectances of the sunlit tree crowns, sunlit background, shaded tree crown, and shaded background. k_j are the proportions of the four components in the instantaneous field of view (IFOV). By using the observed reflectance at nadir and at another angle one can derive the background reflectivity (R_G).

The first condition is that the observations are made along a plane where the target reflectances change little with view angle. The directional dependence of reflectance factors is the greatest in the principal solar plane and decreases fast as the viewing azimuth angle moves away from this plane (Bicheron et al., 1997; Peltoniemi et al., 2005b; Sandmeier & Deering, 1999). MISR is an operational sensor overpasssing the equator at approximately 10:30 local time while descending that provides high quality calibrated multi-angular measurements taken along an oblique plane, not so close to the principal plane (Diner et al., 2002). The influence of BRDF is then minimized and it has been observed that the azimuthal dependency of the reflectance of forest floor in particular is typically not that strong (Peltoniemi et al., 2005b) and forward-scattering reflectances of various targets were shown to be fairly constant (Bacour & Bréon, 2005; Deering et al., 1999; Kaasalainen & Rautiainen, 2005). The reflectance at nadir (n) and another zenith angle (a) can be then expressed by the Eqs. (2) and (3):

$$R_n = R_T \cdot k_{Tn} + R_G \cdot k_{Gn} + R_{ZT} \cdot k_{ZTn} + R_{ZG} \cdot k_{ZGn} \tag{2}$$

$$R_a = R_T \cdot k_{Ta} + R_G \cdot k_{Ga} + R_{ZT} \cdot k_{ZTa} + R_{ZG} \cdot k_{ZGa} \tag{3}$$

Canisius and Chen (2007) originally assumed the shaded reflectivities (i.e. R_{ZT} and R_{ZG}) to be comparatively small and replaced them by a constant value ($R_Z = R_{ZT} = R_{ZG}$) for individual wavelengths. However, Gemmell (2000) observed that reflectances from different shaded crowns could differ up to a factor or two. Pisek et al. (2009) tackled the issue in the new version of the algorithm (Eqs. (2) and (3) and used in this study for the first time with satellite RS data), by expressing shaded components of trees and ground dynamically as functions of their sunlit part and the multiple scattering factor (White et al., 2001, 2002a,b), giving $R_{ZT} = M \cdot R_T$ and $R_{ZG} = M \cdot R_G$, where $M = R_z / R$ for a reference target. Solving Eqs. (2) and (3), the background reflectivity R_G can be then calculated as:

$$R_G = \frac{R_n(k_{Ta} + k_{ZTa} \cdot M) - R_a(k_{ZTn} \cdot M)}{-k_{Tn} \cdot k_{Ga} + k_{Gn} \cdot k_{Ta} + M(-k_{Tn} \cdot k_{ZGa} + k_{Gn} \cdot k_{ZTa} - k_{Ga} \cdot k_{ZTn} + k_{Ta} \cdot k_{ZGn}) + M^2(-k_{ZTn} \cdot k_{ZGa} + k_{ZGn} \cdot k_{ZTa})} \tag{4}$$