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An automated field spectrometer system for studying VIS, NIR and SWIR anisotropy for semi-arid savanna

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ABSTRACT

This paper presents the Dahra field spectrometer system (DAFIS) sited in Senegal, West Africa. DAFIS is a unique system that automatically measures the spectro-directional reflectance properties of a semi-arid savanna in the spectral range of 350–1800 nm, daily from sunrise to sunset. The instrumental setup allows studying surface anisotropy for different phenological phases. First data retrieved from the Dahra field spectrometer system show distinctive patterns of spectrally dependent anisotropic behavior: during the rainy season normalized reflectance was highest around solar noon for small off-nadir observation angles but for observations of large off-nadir angles highest values were found in the morning or evening hours (both forward and backward scatter direction). Anisotropy factors corresponding to MODIS, SPOT and SEVIRI red, near-infrared (NIR) and shortwave-infrared (SWIR) sensor response functions indicated little influence of the anisotropic behavior for savanna but vegetation indices including red/NIR (NDVI) and NIR/SWIR (SIWSI) were found to be sensitive to the view angle (NDVI and SIWSI varied by 5 and 41 %, respectively). Surprisingly, the influence from differences in shading (analyzed by measurements from forward and backward scatter direction) did not have a noticeable impact on the indices (0.2 % and 0.5 % difference for NDVI and SIWSI in the backward and forward scatter direction, respectively). The presented data show the large potential of continuous time series collected with the DAFIS system for monitoring of plant spectro-directional behavior in semi-arid African savanna for quantitative evaluation of satellite or airborne remote sensing data or development of new Earth Observation (EO) based indices and algorithms to monitor vegetation status or stress.

1. Introduction

A large number of remote sensing systems are currently in place to observe the Earth's surface from spaceborne and airborne platforms. A consistent comparison between products is thereby difficult because Earth Observation (EO) data are highly influenced by anisotropic effects (Weyermann, Damm, Kneubühler and Schaepman, 2013). Regular spectral multi-angular measurements from ground-based systems are rare but they could help validating and correcting EO data, better understanding upscaling issues, designing EO-based indices and models for environmental monitoring. Only a handful sites exist where automated hyperspectral field data have been collected.

Gamon, Cheng, Claudio, MacKinney, and Sims (2006), Gamon, Rahman, Dungan, Schildhauer, and Huemmrich (2006) report on an automated tram system consisting of a dual-detector spectrometer mounted on a robotic cart for measuring reflectance in the range of approx. 310–1130 nm over the diurnal cycle. The system was installed within a chaparral ecosystem in California, USA. Leuning, Hughes, Daniel, Coops, and Newnham (2006) describe a multi-angle spectrometer (MAS) system mounted on a tower in Australia. The system measures hourly spectral reflectance of a forest canopy between 300 and 1150 nm at four azimuth angles throughout the year. Hilker, Coops, Nesic, Wulder, and Black (2007); Hilker, Nesic, Coops, and Lessard (2010) describe an automated spectral data collection system named AMSPEC (Automated Multiangular Spectro-radiometer for Estimation of Canopy reflectance) which is installed in Canada. The AMSPEC system is mounted on a tower and measures year round spectral reflectance of a forest canopy between 350 and 1200 nm under different viewing and sun angle conditions. The system is able to sample spectra in a near 360° view around the tower with adjustable viewing zenith angle (Hilker et al., 2007).

Yet, none of the described systems provide measurements in the shortwave-infrared (SWIR) spectral range, which has been shown to be valuable for vegetation water content retrieval (Tucker, 1980). Canopy water stress is the most common limitation to photosynthesis and plant primary productivity at the global scale (Nemani et al., 2003). Near-infrared (NIR)/SWIR based indices have been shown to be promising for monitoring canopy water content (Carter, 1991; Ceccato, Flasse, Tarantola, Jacquemoud, & Grégoire, 2001; Fensholt & Sandholt, 2003; Gao, 1996; Tucker, 1980) which is a key indicator for drought assessments in dryland ecosystems (Wang & Qu, 2007; Zhao

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et al., 2013). Visible (VIS), NIR and SWIR sensitivity to variations in soil moisture, leaf water content and bidirectional reflectance distribution function (BRDF) for vegetated surfaces has been studied using radiative transfer models (Jacquemoud et al., 2009; Latifovic, Cihlar, & Chen, 2003; Wang, Qu, Hao, & Zhu, 2008). However, the effect of bidirectional reflectance factor (BRF) variations on EO-based vegetation indices is currently not well documented for different plant functional types and ecosystems. There is a need for ground-based continuous multi-angular measurements suitable for a direct comparison and validation of EO data products from polar orbiting instruments with sensors influenced by day-to-day variations in sun-target-sensor geometry impacting on the derived vegetation products (Fensholt, Huber, Proud, & Mbow, 2010; Fensholt, Sandholt, Proud, Stisen, & Rasmussen, 2010) or products that provide a characterization of surface anisotropy used to both determine global land surface albedos and nadir view-angle-corrected reflectance (MODIS Surface Reflectance BRDF/Albedo) (Lucht, Schaaf, & Strahler, 2000).

In this paper we present data and the setup of an automated multi-angular field spectrometric system situated in the semi-arid Senegalese Sahel. Unique to this system is that it provides regular spectral measurements of a region with only sparse ground data coverage and that not only VIS and NIR but also the SWIR spectral range is measured. The semi-arid Sahel is characterized by extreme inter-annual variability in rainfall (Nicholson, Dezfuli, & Klotter, 2012) thereby posing one of the biggest obstacles to the achievement of food security in the region (Kandji, Verchot, & Mackensen, 2006). Due to the highly variable climate in the Sahel, temporal continuity in spectro-directional measurements is important to get representative measures on the one hand and to capture key transitions in ecosystem behavior associated with disturbance and stress on the other hand (Gamon, Cheng, Claudio, MacKinney, & Sims, 2006; Gamon, Rahman, Dungan, Schildhauer, & Huemmrich, 2006).

The objective of this paper is twofold: (1) to outline the measurement scheme and set up of the automated multi-angular field spectrometric system and (2) to present first analyses of spectral anisotropy in the spectral range from VIS to SWIR. Two different seasons were analyzed to investigate the impact of anisotropic data on the use of two well-known vegetation indices covering together both VIS/NIR/SWIR wavelengths.

2. Materials and Methods

2.1. The Dahra field site

The field spectrometer system has been installed at the Dahra field site in the semi-arid northern part of Senegal (15.40° N, 15.43° W) (Fensholt & Sandholt, 2005; Fensholt, Sandholt, & Stisen, 2006) (Fig. 1). The savanna ecosystem found at the area is similar to many other parts of the Sahel (Hanan, Prevost, Diouf, & Diallo, 1991). Fine-leaved annual grasses with a maximum height of 60 cm, such as *Schoenefeldia gracilis, Dactyloctenium aegupticum, Aristida mutabilis*, and *Cenchrus bifloures* dominate the herbaceous layer in the region (Valenza & Diallo, 1972), but widely spaced perennial grasses with a maximum height of 80 cm can also be found (Ridder, Stroosnijder, Cisse, & van Kelulen, 1982). Tree and shrub canopy cover generally do not exceed 5% and are dominated by two species: *Balanites aegyptiaca* and *Boscia senegalensis* (Diallo, Diouf, Hanan, Ndiaye, & Prévost, 1991). The soil type can be characterised as poorly developed formed on sandy parent material of dunes or fluvial deposits (less than 3% clay). The rainy season stretches from July to October and precipitation is sparse and intermittent with annual totals ranging from 300 to 500 mm and is thus typical for the Sahelian environment. The Dahra site, where measurements of climate, radiometry and fluxes have been recorded since 2002, is characterized by a uniform vegetation cover (Fig. 1) within a radius of at least 3 km from the fieldwork site to reduce uncertainty in the point to pixel comparison (Fensholt, Huber, Proud, & Mbow, 2010; Fensholt, Sandholt, Proud, Stisen, & Rasmussen, 2010; Fensholt et al., 2006).

2.2. The Dahra field spectrometer system (DAFIS)

The DAFIS was installed in 2011 and consists of two ASD FieldSpec3® spectrometers (ASD Inc., Colorado, USA). While one is mounted on a 12 m mast pointing to the land surface (ASD-FS_{target}), the other one is mounted on a 2 m high stand pointing to a Spectralon panel under a glass dome (ASD-FS_{ref}) (Labsphere Inc., New Hampshire, USA) (Fig. 2). Measurements are acquired at 15-minute intervals (corresponding to the Meteosat Second Generation (MSG) acquisition scheme) from sunrise to sunset and over the entire calendar year. The instruments are

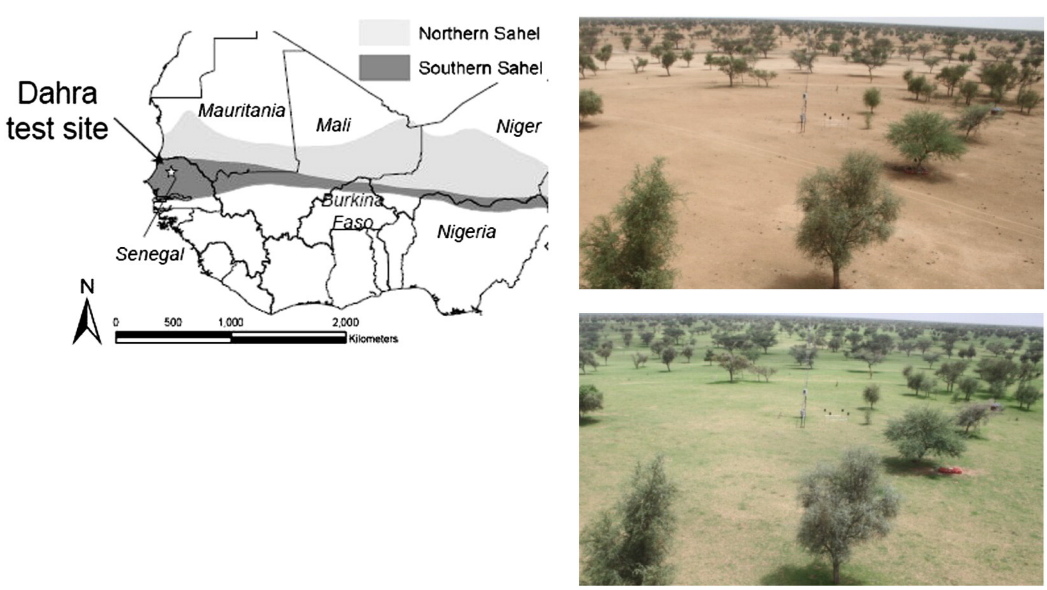

Fig. 1. Location of the Dahra field site (Senegal) in the semi-arid Sahel. The north-southern boundaries of the Sahel can be defined by the 100 mm and 600–800 mm isohyets, respectively. Photographs show the grassland savanna at the Dahra site (taken from south) in the dry season (upper photograph, taken on July 1, 2013) and at the very beginning of the rainy season (lower photograph, taken on August 1, 2013) showing predominantly annual grasses and a tree cover of less than 5 %.