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Importance of biocrusts in dryland monitoring using spectral indices

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ABSTRACT

Multi-temporal remote sensing information and spectral indices have been extensively used in studies to monitor ecosystem functioning and surface-energy budgets. However, most of these indices did not show good results in areas covered by sparse vegetation, like most of the Drylands. In these ecosystems, open spaces between plants are often covered by biological soil crusts (biocrusts), i.e. communities of cyanobacteria, algae, microfungi, lichens, mosses and other microorganisms growing in the uppermost millimeters of the soil. Due to their mostly dark color, biocrusts influence the spectral response of dryland surfaces, making it necessary to assess the sensibility of widely used spectral indices to variations in biocrusts cover. In this study we used spectra of biocrusts, bare soil and vegetation to analyze the effect of biocrust cover on the spectral response of heterogeneous areas. In a second approach we investigated the impact of biocrust water status on spectral characteristics. Based on spectral mixture analysis, we calculated the response of a wide range of vegetation/biocrust/bare soil landscape compositions, obtaining a total of 702 spectra. These were used to calculate the Normalized Difference Vegetation Index (NDVI), the Enhanced Vegetation Index (EVI), the Water Index (WI) and surface albedo, and the effect of biocrust cover and water status on these indices was analyzed. Biocrusts exerted a considerable effect on vegetation indices and surface albedo, whereas WI was mostly affected by vegetation type and cover. As biocrust cover increased, the value of NDVI and EVI also increased, whereas albedo decreased, and these effects were more important under low vegetation cover. Moreover, as biocrusts almost immediately turned dark after water pulses, the effect of biocrust cover on spectral indices increased already 30 min after wetting. Although these results varied depending on vegetation type, they demonstrate, that biocrusts largely affect the spectral response of dryland surfaces, and they illustrate how this effect is reinforced by water. Thus, biocrusts need to be considered in studies analyzing dryland phenology, productivity and water status. Moreover, in order to increase the accuracy of hydrological and climate forecast predictions, biocrust effects on surface albedo, both in a dry and wet stage, need to be included.

1. Introduction

Multispectral imagery from air-borne or space-borne sensors have been extensively used to analyze ecosystem functioning from regional to global scales (Bannari, Morin, Bonn, & Huete, 1995; Oyonarte, Alcaraz-Segura, Oyarzabal, Paruelo, & Cabello, 2010). They provide synoptic coverage data of the land surface and repeated temporal sampling with high potential to monitor spatial and temporal heterogeneity of vegetation water status (Casas, Riaño, Ustin, & Dennison, 2014), phenology (Cabello, Alcaraz-Segura, Ferrero, Castro, & Liras, 2012), dynamics (Garcia, Litago, Palacios-Orueta, Pinzón, & Ustin, 2010), and biogeochemical properties (Ustin, 2013; Dahlin, Asner, & Field, 2013). Most of these studies use spectral indices such as the Normalized Difference Vegetation Index (NDVI; Rouse, Haas, Schell, & Deering, 1973), the Enhanced Vegetation Index (EVI; Huete et al., 2002) or the Water Index (WI; Peñuelas, Piñol, Ogaya, & Filella, 1997) to estimate biomass and net primary production (Paruelo et al., 2005), leaf area (Gong, Pu, Biging, & Larrieu, 2003), crop yield (Sakamoto, Gitelson, & Arkebauer, 2014), water stress (Olsen, Stisen, Proud, & Fensholt, 2014), and evapotranspiration and canopy water content (Tang, Li, & Tang, 2010; Casas et al., 2014) among other important plant functional traits (Dahlin et al., 2013). Moreover, during the past decades land surface parameters obtained from multi-temporal remote sensing observations like surface albedo, vegetation cover, leaf area and absorbed photosynthetically active radiation developed into critical parameters in surface-energy budgets, which have been mainly used for land surface process simulations and hydrological and climate forecast models (Campra, Garcia, Cantón, & Palacios-Orueta, 2008). Most of these indices are highly sensitive to biophysical variations in moderately and densely vegetated areas like forests and croplands, but have low dynamic ranges in sparsely vegetated drylands (Wu, 2014). These ecosystems are characterized by low vegetation cover interspersed by a heterogeneous, seemingly bare ground matrix (Reynolds et al., 2007). However, superficially bare-looking areas of drylands around the world are often covered by complex communities of cyanobacteria, algae, microfungi, lichens,

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mosses and other microorganisms, which grow in intimate association within the uppermost millimeters of the soil surface (Belnap & Lange, 2003). These communities, commonly known as biological soil crusts or biocrusts, improve numerous soil surface properties (Chamizo, Cantón, Miralles and Domingo, 2012a) and control key ecosystem processes like nitrogen and carbon fixation (Elbert et al., 2012), infiltration and evapotranspiration (Chamizo et al., 2015) and soil erosion (Rodriguez Caballero et al., 2015a).

Detailed spectral analyses of biocrusted surfaces have shown two main absorption features at 500 and 679 nm, which are related to the presence of carotenoids and chlorophyll a (Karnieli et al., 1996; Weber et al., 2008; Ustin et al., 2009; Chamizo et al., 2012b; Rodríguez-Caballero, Escribano, & Cantón, 2014), a decrease in surface reflectance (Zaady, Karnieli, & Shachak, 2007; Zhang, Wang, Hu, Pan, & Zhang, 2014), and an increase in the value of vegetation indices (Fischer et al., 2012) and emissivity (Rozenstein & Karnieli, 2015; Rozenstein et al., 2015). These differences in spectral response between biocrusts and bare areas or vegetation, combined with the fact that biocrusts cover up to 70% of dryland surfaces, may exert a strong impact on the spectral signal of dryland surfaces from regional to global scales (Rozenstein & Karnieli, 2015). In addition, biocrusts and vegetation show phenological differences, as changes in greenness or water status in biocrusts exert different effects on spectral response than variations in vegetation phenology (Karnieli, 2003). Thus, the sensibility of frequently used spectral indices for variations in biocrust cover and water status need to be assessed in order to be considered in multi-temporal spectral analyses of dryland functioning and land degradation studies and to increase the accuracy of hydrological and climate forecast predictions. In this study we i) analyze the effects of biocrust cover and water status on the spectral response of typical heterogeneous dryland surfaces, and ii) quantify how these effects modify the value of some of the most widely used broad-band spectral indices, like the NDVI, EVI, WI and surface albedo.

2. Material and methods

Sample collection and spectral field measurements were conducted in the vicinity of the former BIOTA observatory Soebatsfontein (No. 22; 30° 10′ 58.9″ S, 17° 33′ 2.1″ E, elevation: 262 m a.s.l.; www.Biota-Africa.org), located in the Succulent Karoo, Northern Cape Province, South Africa, in September 2004. This is a semiarid desert with shallow sandy soils covered by a dense pattern of biocrusts (about 30% coverage), being composed of cyanobacteria-dominated with minor amounts of chlorolichen- and bryophyte-dominated biocrusts (Weber et al., 2008; Büdel et al., 2009; Weber, Graf, & Bass, 2012). The vegetation is dominated by a unique flora of succulent plants (Van-Jaarsveld, 1987).

Spectral reflectance of vascular plants was measured in the field. To do that, twigs of frequent and characteristic plant species, i.e. *Atriplex lindleyi* spp. *inflata*, *Cephalophyllum inaequale*, and *Ruschia cyathiformis* were cut and placed on a dark cardboard, forming a dense layer of green material so that the background was hardly visible. The three plants were carefully picked, as they characterize different plant morphologies and growth forms with *A. lindleyi* ssp. *inflata* being an annual plant of about 30–40 cm height with small bluish-green leaves and a powdery appearance, *C. inaequale* being a soil-creeping plant with large dark green to reddish succulent leaves, and *R. cyathiformis* being a shrub with small succulent vividly green leaves. Surface reflectance measurements were conducted with a UV–VIS–NIR-spectrometer S2000 (Ocean Optics Inc., EW Duiven, Netherlands), with spectral resolution increments (FWHM) of 0.3–10 nm covering a range of 200 to 1100 nm at an opening angle of 25° (FOV). However, due to measurement noise in the UV and a substantial decrease of sensor sensitivity above 1000 nm, only the wavelength range between 400 and 950 nm was used for analysis. Measurements were conducted at an integration time of 6–8 nm and the results represent average values of 50 measurements. The spectrometer was operated with the accompanying software OOIBase32, version 2.0.1.4 (Ocean Optics Inc.) running on an external laptop. Prior to each measurement, a light and dark reference was taken. Measurements were made at a distance of about 50 cm, resulting in a measured area of about 25 cm diameter. Each plant was measured five times from slightly varying positions and mean values of the spectra were used to characterize each plant.

For spectral measurements in the laboratory, cyanobacteria-, chlorolichen- and moss-dominated biocrusts as well as bare soil samples were collected with petri dishes (85 mm diameter) following the procedure described in Weber et al. (2008), and then transported to the University of Kaiserslautern, where they were stored in the freezer until spectral measurements (no longer than 5 months) to avoid bleaching of the pigments. At least 24 h before measurements the samples were taken out of the freezer to adapt to environmental conditions. This method is well established and has been shown to have no negative effects on the photosynthetic properties of biocrust organisms (Kappen & Lange, 1970). Laboratory measurements were conducted with the same instrumental setup as used in the field. During lab measurements, an integrating sphere containing an integrated halogen lamp (ISP REF Integrating Sphere, Ocean Optics B.V., Duiven, Netherlands) was connected to the fiber optic cable to ensure homogeneous illumination of the sample. The halogen bulb, which covers a wavelength range of 360–1000 nm, was turned on at least 30 min prior to the experiments to guarantee constant light conditions. For measurement of biocrusts and bare soil, the samples were put on a dark surface and covered with a petri dish lid with five circular holes (15 mm diameter). The integrating sphere (8 mm opening) was subsequently placed on the five holes for measurements in order to cover the small-scale spectral variation within each biocrust type. The distance between the integrating sphere and the sample ranged between 1 and 3 mm, resulting in a measuring area of 8.4–9.2 mm in diameter. The mean value of the five spectra was used as a representative spectrum of the biocrust type or bare soil.

To analyze the effect of wetting on the biocrust spectra, and the increase in chlorophyll content after one week under wet conditions, cyanobacteria-dominated biocrusts were watered with distilled water and kept wet for one week at 22–30 °C and a photosynthetic photon flux density (PPFD) of 150–300 μmol m^{-2} s^{-1} at a light–dark cycle of 12/12 h. The spectral response was measured at three different time steps, i) prior to wetting under completely dry conditions, ii) under saturated water conditions 30 min after wetting, and iii) under saturated water conditions one week after initial wetting. After initial wetting to full saturation, the samples were placed in a closed chamber with only small ventilation holes to keep the samples homogeneously wet over the whole time span (i.e. 30 min and 8 days respectively). Thus, the saturating water content remained stable over the whole experiment. We had selected these three water stages to analyze if biocrust water content modifies the value of the different spectral indices. Most of the year, the biocrusts are in a dry stage. Sometimes, however,

Table 1
Spectral indices calculated for the spectral dataset including their acronym, mathematical formula and reference.

Index	Acronym	Equation	Author
Normalized Difference Vegetation Index	NDVI	(NIR − RED) / (NIR + RED)	Rouse et al. (1973)
Enhanced Vegetation Index	EVI	2.5 × (NIR − RED) / (NIR + 6RED − 7.5BLUE + 1)	Huete et al. (2002)
Water Index	WI	(R900 / R970)	Peñuelas et al. (1997)
Albedo	ρ	Mean $R_{(400–1100)}$	Liang (2001)