ISPRS Journal of Photogrammetry and Remote Sensing 126 (2017) 94–107

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

journal homepage: www.elsevier.com/locate/isprsjprs

Transferability of multi- and hyperspectral optical biocrust indices

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ARTICLE INFO

Article history:
Received 31 August 2016
Received in revised form 3 December 2016
Accepted 12 February 2017

Keywords:
Biological soil crust
Remote sensing
Hyperspectral
Mapping indices
Drylands
Multispectral

ABSTRACT

Biological soil crusts (biocrusts) are communities of cyanobacteria, algae, microfungi, lichens and bryophytes in varying proportions, which live within or immediately on top of the uppermost millimeters of the soil in arid and semiarid regions. As biocrusts are highly relevant for ecosystem processes like carbon, nitrogen, and water cycling, a correct characterization of their spatial distribution is required. Following this objective, considerable efforts have been devoted to the identification and mapping of biocrusts using remote sensing data, and several mapping indices have been developed. However, their transferability to different regions has only rarely been tested. In this study we investigated the transferability of two multispectral indices, i.e. the Crust Index (CI) and the Biological Soil Crust Index (BSCI), and two hyperspectral indices, i.e. the Continuum Removal Crust Identification Algorithm (CRCIA) and the Crust Development Index (CDI), in three sites dominated by biocrusts, but with differences in soil and vegetation composition. Whereas multispectral indices have been important and valuable tools for first approaches to map and classify biological soil crusts, hyperspectral data and indices developed for these allowed to classify biocrusts at much higher accuracy. While multispectral indices showed Kappa (κ) values below 0.6, hyperspectral indices obtained good classification accuracy ($\kappa \sim 0.8$) in both the study area where they had been developed and in the newly tested region. These results highlight the capability of hyperspectral sensors to identify specific absorption features related to photosynthetic pigments as chlorophyll and carotenoids, but also the limitation of multispectral information to discriminate between areas dominated by biocrusts, vegetation or bare soil. Based on these results we conclude that remote sensing offers an important and valid tool to map biocrusts. However, the spectral similarity between the main surface components of drylands and biocrusts demand for mapping indices based on hyperspectral information to correctly map areas dominated by biocrusts at ecosystem scale.

1. Introduction

Dryland regions cover about 40% of the global land surface (Reynolds et al., 2007). Due to the extreme scarcity of water resources in these areas and the increasing human population, desertification and land degradation, enforced by climate change and human activities, are some of the greatest environmental challenges in the XXI century (Safriel et al., 2005). Drylands comprise a sparse and often patchy vegetation cover, (Ludwig et al., 2005; Puigdefábregas, 2005). The undisturbed areas between vascular plants and shrubs are often covered by biocrusts, which are associations of soil particles with complex communities of cyanobacteria, green algae, lichens, and mosses with heterotrophic microfungi, archaea, and other bacteria (Weber et al., 2016). These biocrust communities occur in drylands throughout the world and cover up to 40–100% of the open ground surface, being considered an important surface component in hot, cool, and cold arid and semi-arid regions around the world (Bowker et al., 2011; Maestre et al., 2011; Pointing and Belnap, 2012). Although biocrusts represent an insignificant fraction of the soil profile, they modify soil texture and porosity (Miralles-Mellado et al., 2011; Felde et al., 2014), controlling runoff generation (Rodríguez-Caballero et al., 2013), evaporation (Zhang et al., 2008; Chamizo et al., 2013) and water availability for vascular vegetation and microorganisms

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http://dx.doi.org/10.1016/j.isprsjprs.2017.02.007

(Chamizo et al., 2016a,b). They bind soil particles, increasing soil cohesion (Thomas and Dougill, 2007), stability (Zhao et al., 2014), and micro-topography (Rodríguez-Caballero et al., 2012), reducing water and wind erosion (Chamizo et al., 2012a; Belnap et al., 2014; Zhao et al., 2014) and providing stable environments for vascular plants (Luzuriaga et al., 2012) and the higher trophic levels (Bamforth, 2008). Moreover, they make significant contributions to the primary production of drylands, serving as nitrogen and carbon sources (Elbert et al., 2012; Porada et al., 2013, 2014) and contributing to the maintenance of multiple ecosystem functions (Maestre et al., 2012).

Given the importance of biocrusts on ecosystem functions and services (Concostrina-Zubiri et al., 2016), and considering their susceptibility to anthropogenic disturbances (Scutari et al., 2004) and global change (Johnson et al., 2012; Ladrón de Guevara et al., 2014; Reed et al., 2016), their conservation has become an important consideration in land management decisions (Belnap et al., 2014; Büdel et al., 2014). However, due to the scarce information on factors controlling biocrust distribution, as they only have been mapped in few ecosystems, their inclusion in management programs is still quite limited.

With the objective of mapping areas dominated by biocrusts, considerable effort has been devoted to the identification of the main spectral characteristics of biocrusts (Graetz and Gentle, 1982; Green, 1986; O'Neill, 1994; Pinker and Karnieli, 1995; Karnieli et al., 1996; Weber et al., 2008; Ustin et al., 2009; Chamizo et al., 2012b; Weber and Hill, 2016). Published studies have described two main absorption features of biocrusts at 516 and 679 nm, related to the presence of carotenoids and chlorophyll *a*, respectively (Weber et al., 2008; Chamizo et al., 2012b; Weber and Hill, 2016), a decrease in reflectivity on the visible region of the spectra (Zaady et al., 2007; Fang et al., 2015; Rodríguez-Caballero et al., 2015; Weber and Hill, 2016), and an increase in emissivity at longer wave lengths as crust cover and developmental stage increases (Rozenstein and Karnieli, 2015). Spectral differences between biocrusts, vegetation and bare soil have been used to map areas dominated by biocrusts (Karnieli, 1997; Chen et al., 2005; Weber et al., 2008; Moghtaderi et al., 2011; Chamizo et al., 2012b; Alonso et al., 2014; Rozenstein and Karnieli, 2015) and to quantify their relative cover (Hill et al., 1999; Rodríguez-Caballero et al., 2014a). These studies have resulted in the development of several biocrust mapping indices using optical reflectivity (Karnieli, 1997; Chen et al., 2005; Weber et al., 2008; Chamizo et al., 2012b). The Crust Index (CI; Karnieli, 1997) and the Biological Soil Crust Index (BSCI; Chen et al., 2005) use multispectral optical information from LANDSAT ETM + images to identify areas dominated by biocrusts in sandy desert ecosystems. Whereas CI was developed for the detection of cyanobacteria-dominated areas, based on the assumption that phycobilins of cyanobacteria cause increased reflectance values in the blue region, BSCI used the slope between the green and red part of the spectrum to discriminate lichen-dominated biocrusts against vegetation and bare sand. Application of these indices in complex and heterogeneous areas, like most drylands, where the surface is covered by a mixture of green and dry vegetation, bare soil, rocks and physical and biological soil crusts, does not provide satisfactory results (Weber et al., 2008; Alonso et al., 2014). This is mainly caused by the subtle spectral differences between the areas covered by sparse vegetation and biocrusts (Escribano et al., 2010). Biocrust mapping indices using optical hyperspectral information, as the Continuum Removal Crust Identification Algorithm (CRCIA; Weber et al., 2008), and the Crust Development Index (CDI; Chamizo et al., 2012b) can identify these subtle spectral differences, thereby improving the ability of remote sensing data to identify areas dominated by biocrusts in drylands (Weber et al., 2008; Chamizo et al., 2012b; Alonso et al., 2014). Moreover, CDI discriminates between different biocrust types and developmental stages, which is crucial, as the effect of biocrusts on most soil surface properties and ecosystem processes depends on biocrust developmental stage.

All existing biocrust mapping indices have been developed for a specific area and biocrust type. Some authors suggested a specific calibration previous to an application of the indices in other study areas, but a description of the methodology necessary to conduct this calibration has not been given (Alonso et al., 2014). For this reason, the transferability of the published indices to areas different to those where they have been developed has only rarely been checked (Weber et al., 2008; Alonso et al., 2014) and needs to be assessed.

The objective of the present study is to highlight the strengths and weaknesses of all indices published in the literature, i.e. (i) the Crust Index (CI), (ii) the Biological Soil Crust Index (BSCI), (iii) the Continuum Removal Crust Identification Algorithm (CRCIA), and (iv) the Crust Development Index (CDI) and to identify the best calibration strategy for each index. To achieve this, we used hyperspectral remote sensing imagery of three areas dominated by different types of biocrusts, to apply the four different algorithms with different calibration values and analyzed the mapping results by means of ground-truthing data. The transferability of the indices and possible modifications of them to develop a universal methodology for biocrust mapping are discussed.

2. Study areas

This study was conducted in three different areas where biocrusts are well represented, varying in parent material, semiarid vascular vegetation (for simplicity called "vegetation" throughout the text) and biocrust composition.

2.1. El Cautivo experimental area

El Cautivo experimental area is located in the Tabernas Desert province of Almería, south-eastern Spain (N37°00′37″ W2°26′30″, elevation: 345 m a.s.l.; Fig. 1a). Climate in El Cautivo has been defined as Thermo-Mediterranean semiarid with an average temperature of 18.5 °C, a mean annual potential evapotranspiration of 1500 mm and a mean annual precipitation of 226 mm, which was measured over a period of 30 years, revealing a high intra- and inter-annual variability (Rodríguez-Caballero et al., 2014b). El Cautivo is a badlands system with silty loam soils, mainly Leptosols, Regosols and Gypsisols (Cantón et al., 2003). The landscape is composed of scarce vegetation embedded in a heterogeneous non-vegetated matrix dominated by biocrusts and physical soil crusts (Cantón et al., 2003). Biocrusts are mainly composed of lichens and cyanobacteria and may cover up to 40% of the whole study area (Supplementary material 1.a).

2.2. Las Amoladeras experimental area

Las Amoladeras experimental area is located in the Cabo de Gata-Nijar Natural Park, province of Almería, south-eastern Spain (N36°50′1″ W2°15′8″, elevation: 90 m a.s.l.; Fig. 1b). Climate at Las Amoladeras is also semiarid, with an average temperature of 18 °C, a mean annual evapotranspiration of 1370 mm and mean annual precipitation of 200 mm (López-Ballesteros et al., 2017). This area is flat and soils are classified as Calcaric Leptosols and Haplic Calcisols with a sandy loam texture. Vegetation consists of sparsely distributed shrubs with biocrusts, mainly dominated by cyanobacteria, lichens and mosses, in the free interspaces (Supplementary material 1.b).