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A review of progress in identifying and characterizing biocrusts using proximal and remote sensing

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ABSTRACT

Biocrusts are critical components of desert ecosystems, significantly modifying the surfaces they occupy. The mixture of biological components and soil particles that form the crust, in conjunction with moisture, determines the biocrusts' spectral signatures. Proximal and remote sensing in complementary spectral regions, namely the reflective region, and the thermal region, have been used to study biocrusts in a non-destructive manner, in the laboratory, in the field, and from space. The objectives of this review paper are to present the spectral characteristics of biocrusts across the optical domain, and to discuss significant developments in the application of proximal and remote sensing for biocrust studies in the last few years. The motivation for using proximal and remote sensing in biocrust studies is discussed. Next, the application of reflectance spectroscopy to the study of biocrusts is presented followed by a review of the emergence of high spectral resolution thermal remote sensing, which facilitates the application of thermal spectroscopy for biocrust studies. Four specific topics at the forefront of proximal and remote sensing of biocrusts are discussed: (1) The use of remote sensing in determining the role of biocrusts in global biogeochemical cycles; (2) Monitoring the inceptive establishment of biocrusts; (3) Identifying and characterizing biocrusts using Longwave infrared spectroscopy; and (4) Diurnal emissivity dynamics of biocrusts in a sand dune environment. The paper concludes by identifying innovative technologies such as low altitude and high resolution imagery that are increasingly used in remote sensing science, and are expected to be used in future biocrusts studies.

Contents

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1. Introduction: biocrust – definition, role and importance

Biocrusts are a type of thin, desiccation tolerant microbial mat of cyanobacteria, subsequently colonized by mosses and lichens, living at the soil surface in drylands (Bowker and Belnap, 2008). Composed of photoautotrophic organisms and soil particles, they act as ecosystem engineers (Jones et al., 1997), and are often associated with increased soil nutrient and water retention—resources that are highly limiting to plant productivity in arid and semi-arid ecosystems. Principal functions of biocrusts include carbon and nitrogen fixation (Barger et al., 2016; Sancho et al., 2016), redistributing of water through reshaping the surface hydrology (Chamizo et al., 2016), and complex interactions with vascular plants (Zhang et al., 2016). One of the most important functions of biocrusts is stabilizing the soil surface against wind and water erosion (Belnap and Büdel, 2016; Chamizo et al. 2017). While doing so, biocrusts are highly susceptible to compressional forces, such as those generated from foot and vehicle traffic associated with grazing, ground-based military training, and recreational activities (Belnap, 1990; Zaady et al., 2016). Due to the functional importance of biocrust communities to the ecological functioning of dryland ecosystems, there is significant interest in studying these communities to better understand their role in this environment (Bowker et al., 2010; Maestre et al., 2011; Maestre et al., 2012).

After decades of studies, a significant amount of information is already known about biocrusts. For instance, the duration of biocrust successional development and the nature of its microphytic composition at a late successional stage are heavily affected by the amount of precipitation as well as the time passed since the last disturbance of the surface (Belnap et al., 1994). For instance, in the Negev desert, in areas where annual precipitation is less than 100 mm, biocrusts are 1–2 mm thick, while in areas where the precipitation is about 300 mm, biocrusts can reach up to a thickness of 15 mm (Zaady et al., 1997). Cyanobacteria biocrusts are the earliest stage of the succession that mainly appears in arid areas. Moss and lichen rich biocrusts are established, however, in areas with over 200 mm of annual precipitation. The biocrusts' effect on their environment is largely influenced by the composition of the microphytic community (Belnap, 2001; Barger et al., 2006; Wu et al., 2009). However, biocrusts of all kinds are important components of the ecosystem that significantly modify the surfaces they cover. Biocrusts are mostly the subject of field studies in small plots, from which samples are often removed for laboratory analysis, as well as regional monitoring by proximal and remote sensing means (Bu et al., 2013).

In an early review regarding remote sensing of biocrusts in 2001, the authors state that "despite the global extent of soil crusts and the expanding interest in their ecological roles, there have been relatively few studies published on the use of remote sensing to detect and map their distributions" (Karnieli et al., 2001). While progress has been made since then, this notion still holds true, and is re-iterated from time to time (e.g. Duane Allen, 2010). The journey to discover the links between microbial community structure and terrestrial surface biosphere observations has only just began (Hamada et al., 2014). Over time, the topic of biocrust remote sensing has been partially covered, but not exhausted, in other reviews (e.g. Li et al., 2014; Weber and Hill, 2016). The objective of this review is to present the spectral characteristics of biocrusts across the optical domain, and to discuss some of the most significant developments in the application of proximal sensing for biocrust studies since the first major review on this subject in 2001 (Karnieli et al., 2001). In their review, Karnieli et al. discuss the first studies from the 1990s that applied proximal reflectance spectroscopy and remote sensing to map biocrusts, higher plants, and bare soil, based on their spectral reflectance. These studies focused primarily on case studies from Israel and the United-States, and while the study of biocrusts is still ongoing in these countries, remote sensing has since been used to study biocrusts in many other places (Table 1). On top of land cover mapping which was the primary focus of early investigations, proximal and remote sensing have been employed to tackle some of the main knowledge gaps in the study of biocrusts formation and their functions in the ecosystem. Some of these aspects were covered in a recent review (Weber and Hill, 2016) that conducted a methodical review of chromophores in the reflective region and of spectral processing techniques adapted to enhance the spectral signal from biocrusts. In addition to reflectance which was used early on, thermal data has since emerged as a significant tool for identification and characterization of biocrusts. However, the review by Weber and Hill (2016), which covered progress made until 2014, neglected to cover recent advancements in thermal and high temporal resolution studies of biocrusts. Therefore, this review will discuss these latest advancements in detail. The scope of the paper is defined as follows: Section 2 will discuss the motivation for using proximal and remote sensing in biocrust studies. Section 3 will discuss the application of reflectance data to the study of biocrusts. Section 4 will discuss the technological developments that facilitate the application of thermal data for biocrust studies. Section 5 will focus on four specific knowledge gaps at the forefront of proximal and remote sensing of biocrusts. Finally, Section 6 will offer conclusions and future outlooks on the topic.

Table 1
Geographic locations of studies employing proximal and remote sensing for biocrust applications since 2001.

Region	References
Australia	Eisele et al. (2012, 2015);
Israel	Amir et al. (2014); Burgheimer et al. (2006a,b); Dall'Olmo and Karnieli (2002); Karnieli and Dall'Olmo (2003); Karnieli et al. (2002); Paz-Kagan et al. (2014b); Qin et al. (2005, 2002a,b, 2006, 2001); Rozenstein and Karnieli (2015); Rozenstein et al. (2015b, 2016, 2014); Schmidt and Karnieli (2000); Schmidt and Karnieli (2002); Zaady et al. (2007); Hill et al. (2008);
North-America	Couradeau et al. (2016); Hamada and Grippo (2015); Neta et al. (2010; Neta et al. (2011); Ustin et al. (2009); Li et al. (2015);
Southern Africa	Weber et al. (2008); Rodríguez-Caballero et al. (2015);
China	Chen et al. (2005); Fang et al. (2015); Zhang et al. (2014);
Central Asia	Maman et al. (2011);
Spain	Chamizo et al. (2012); Rodríguez-Caballero et al. (2014);
Iran	Moghtaderi et al. (2011);
Boreal	Yuan et al. (2014);

2. Why use proximal and remote sensing to study biocrusts?

An assortment of destructive analysis techniques has been demonstrated for determining the biocrust's level of development. These methods include field and laboratory testing such as measuring crust thickness using vernier caliper, and measuring hardness using a soil penetrometer to measure resistance to compressive force (McKenna Neuman and Maxwell, 2002; Zaady and Bouskila, 2002; Langston and McKenna Neuman, 2005; Laureen Drahorad and Felix-Henningsen, 2012). These methods rely on the thickness and hardness of biocrusts to increase with their successional development. Other laboratory methods are able to infer the biocrust's successional stage based on phospholipid fatty acid, or denaturing gradient gel electrophoresis (Zaady et al., 2010; Ben-David et al., 2011), phytomass of algae and lichens (West, 1990) or quantifying chlorophyll, polysaccharide, and protein content (Zaady and