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 tentative 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.

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Contents

1. Introduction: biocrust – definition, role and importance .......................................................... 246
2. Why use proximal and remote sensing to study biocrusts? ....................................................... 246
3. Reflectance spectroscopy ........................................................................................................... 247
4. TIR spectroscopy ..................................................................................................................... 249
5. Closing the research gaps .......................................................................................................... 250
  5.1. Role of biocrusts in biogeochemical cycles ............................................................... 250
  5.2. Monitoring the tentative establishment of biocrusts ................................................... 250
  5.3. LWIR spectroscopy for identification and characterization of biocrusts ............... 251
  5.4. Diurnal emissivity dynamics of biocrusts in a sand dune environment .......... 252
6. Summary and future outlook .................................................................................................... 252
Acknowledgments .......................................................................................................................... 253
References ..................................................................................................................................... 253

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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 begun (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 the progress happening 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.

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 Drahord 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

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**Table 1**

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<th>Region</th>
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<td>Australia</td>
<td>Eisler et al. (2012, 2015); Amiri et al. (2014); Burghheimer 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); Couradeau et al. (2016); Hamada and Grippo (2015); Neta et al. (2016; Neta et al. (2011); Ustin et al. (2009); Li et al. (2015); Weber et al. (2008); Rodríguez-Caballero et al. (2015); Chen et al. (2005); Fang et al. (2015); Zhang et al. (2014); Maman et al. (2011); Chamizo et al. (2012); Rodríguez-Caballero et al. (2014); Moghadam et al. (2011); Yuan et al. (2014);</td>
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Bouskila, 2002). While these techniques are all valid and accepted ways of estimating a biocrust’s successional stage, they all require disturbance of the soil surface by removing the crust for laboratory analyses.

Other ways to analyze biocrusts without disturbance are by using the visual index of biocrust development (Belnap et al., 2008), and proximal reflectance spectroscopy (Zaady et al., 2007). While visual assessment of biocrusts development corresponds reasonably well with chlorophyll a, polysaccharide content, and soil stability, it is only applicable to specific regions (since it was originally developed for cool deserts in the US). On the other hand, reflectance spectroscopy is employed for qualitative and quantitative analysis of various targets (Milton et al., 2009; Pimstein et al., 2011), and its rapid and accurate application in soil studies presents an alternative to the traditional “wet” laboratory analyses (Nocita et al., 2015). Whereas most spectral soil evaluations have been performed under controlled laboratory conditions, field applications are now rapidly gaining an important role in soil spectroscopy (Ben-Dor et al., 2009; Cécillon et al., 2009; Rozenstein et al., 2015a). Moreover, spectroscopic knowledge acquired from close proximity can be upscaled by remote sensing, to detect and map the distribution of biocrusts, extending site-specific ecological studies to a regional scale, thus reducing the time and cost associated with ground surveys (Karnieli et al., 2001; Liang, 2007). The spectral signal of biocrusts under wet conditions can be similar to that of higher plants, producing relative high values of Normalized Difference Vegetation Index (NDVI, Tucker, 1979). Accordingly, in drylands, careful attention should be given to the interpretation of vegetation signal from remote sensing images. The signal from biocrusts is usually dominant in the beginning of the rainy season when the annuals have not germinated yet and the perennials are still dry (e.g. Karnieli, 2003). Therefore, wrong interpretation of the vegetation phenology can further lead to wrong conclusions about the ecology, biodiversity, pedology, and other site characteristics. Two distinct spectral techniques are prevalent in soil and vegetation analysis and are therefore relevant to biocrusts and other land covers characterization (Fig. 1):

1) Reflectance spectroscopy in the visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) regions is a well-established source of rich information about the composition of the Earth’s surface (Hunt, 1977; Kokaly et al., 2009; Ben-Dor et al., 2009; Nocita et al., 2015). Remote sensing in that region usually relies on measuring the solar illumination that is reflected back from the earth’s surface.

2) Thermal infrared (TIR) spectroscopy is currently less common as a field method since instrumentation is more expensive and not widely available (Ribeiro da Luz and Crowley, 2007, 2010). However, recently it was shown to have increased sensitivity for various soil properties over the reflective spectral region, and in addition, the inherent self-emission associated with the TIR allows remote sensing also from shaded targets, under cloud cover, and even during the night (Eisele et al., 2012; Eisele et al., 2015).

3. Reflectance spectroscopy

The relative amounts of energy reflected from surfaces such as soil, plants, and biocrusts vary as a function of wavelength. The most important factor affecting soil reflectance is the soil mineralogy (e.g., iron oxides, clay minerals, and carbonates), with additional effect due to soil water content, organic matter content, soil texture, and soil roughness (Viscarra Rossel et al., 2006; Paz-Kagan et al., 2014a). The reflectance spectrum of vegetation, however, is mainly influenced by different factors such as pigments and leaf structure. Typically, healthy green vegetation shows an extreme difference in reflectance between the VIS (very low reflectance) and the NIR (relatively high reflectance). This is due to the leaf of a plant being a primary photosynthesizing organ, with photosynthesis occurring in the chloroplasts, where the chlorophyll pigment is located. Important absorption pigments of different plants are described in the literature (Cates et al., 1965; Reyer, 1998). However, most leaves contain a combination of chromophores (and the absorption peaks are broad) so that the resulting reflectance spectrum does not have sharply defined peaks. Fig. 2 shows the reflectance of soil and vegetation that illustrates the separate reflectance properties of green plants in the VIS and NIR. The presence of chlorophyll in green plants causes a strong absorption of light in the blue and red wavelengths and the reflectance plot shows the ‘red edge’ feature at about 0.68 μm, where the reflectance rises from the red towards the NIR (Karnieli et al., 2001). The relatively high reflectance of green leaves in the NIR is mainly controlled by the leaf structure and the proportion of air spaces’ area in the spongy mesophyll’s area (Rapaport et al., 2014).

The spectral signature of biocrusts is similar to both soil and vegetation. This duality is the result of dormancy and activity states of the microphytes in the biocrust. Cyanobacteria belonging to the genus Microcoleus vaginatus for instance, are able to migrate down from the surface (using a hygroscopic mechanism) when dry to a depth of about 2 mm, and rise back up when wet. This phenomenon is visible as the soil surface changes its color into green when wet within minutes to hours (Campbell, 1979). Many desert mosses close their leaves when dry. The lichen Collemia spp., in which a fungus coexists with a Nostoc spp. cyanobacteria, appears as a collection of scattered black dots on the surface, covering several millimeters; when wet, they spread and cover the spaces between them and show as dark green (Zaady, 1999). Hence, biocrusts often appear as soil when dry and as vegetation by conducting photosynthesis when wet. Fig. 2 captures this ambivalence. The spectral properties of biocrusts were first presented for Australia (O’Neill, 1994) and shortly after for Israel (Karnieli and Tsoar, 1995; Pinker and Karnieli, 1995). It was noted that the chlorophyll signal from biocrusts may be misinterpreted from remote sensing imagery as a signal from higher vegetation, leading to misinterpretation in ecosystem productivity and vegetation dynamics (Karnieli and Sarafis, 1996; Yuan et al., 2014; Fang et al., 2015). At the same time, the albedo from biocrusts may be different than the soil substrate. For example, biocrusts often have lower albedo than that of the underlying bright substrate (Karnieli and Tsoar, 1995; Zhang et al., 2014).

Biocrusts’ reflectance is explained by absorption features of organic components (Karnieli and Sarafis, 1996; Karnieli et al., 1999, 2001; Ustin et al., 2009; Escribano et al., 2010): 0.430 μm (phytocyanins in cyanobacteria), 0.680 μm (chlorophyll in phototrophic members of biocrust), 1.720 μm (cellulose and lignin), 2.080 μm (starch, lignin, and wax), and 2.309 μm (humic acid, wax, and starch). However, biocrusts from different successional stages and from different parts of the world present slightly different spectral features (Weber and Hill, 2016). Much like soil and plants, water content also affects the reflectance spectrum of biocrusts. The NIR and SWIR regions were used to monitor the moisture content of biocrusts in subarctic peatlands and linking these surface properties to the water table position (Neta et al., 2010, 2011). However, water absorption features are not indicative of the biocrust microphytic composition, nor of their photosynthetic activity. Different biocrust compositions or different development levels do produce noticeably different spectral signatures, especially when measured in high spectral resolution (hundreds of continuous narrow bands), or hyperspectral resolution (Karnieli et al., 1999; Zaady et al., 2007; Ustin et al., 2009; Chamizo et al., 2012). While these differences are not always retained when measuring them in the field, rather than
laboratory conditions (Ustin et al., 2009), field measurements can correspond well to spectral signatures derived from hyperspectral airborne images (Rodríguez-Caballero et al., 2014).

The spectral effect of biocrust cover on the reflectance measured by satellite imagery was observed to be different from that of bare soil as early as the 1980’s (Graetz and Tongway, 1986). The spectral signature of biocrusts was acknowledged to be significant for studies of soil moisture and desertification, and therefore it was suggested to warrant a quantitative analysis (West, 1990). Later on, several spectral indices were created to facilitate the mapping of biocrust cover, by enhancing the signal of cyanobacteria dominated biocrusts (Karnieli, 1997; Moghtaderi et al., 2011) and lichen dominated biocrusts (Chen et al., 2005) using multispectral remote sensing. Multispectral imagery was also used for land cover classification of biocrusted areas (Qin et al., 2006; Maman et al., 2011; Paz-Kagan et al., 2014b). Additionally, several studies used hyperspectral imagery to map biocrusts; these studies identified biocrusts as distinguished from other land cover types (Weber et al., 2008; Rodríguez-Caballero et al., 2014), or classified different treatments, such as irrigation and disturbance (Ustin et al., 2009). Most studies to date used tailor-made approaches for regional mapping of biocrusts, yet, there is no universal methodology for mapping biocrusts. Achieving this is not a trivial task since biocrust reflectance depends on the microphytic community composition, the composition of the soil substrate, and the phenological state of the biocrusts as well as the higher vegetation at the time of measurement.

For this reason, attempts to generalize findings from one site to a different one need to be carried out with great caution, otherwise interpretation of the spectral data can lead to erroneous conclusions. Recently, one study analyzed the effects of biocrust cover and water status on the spectral response of heterogeneous dryland surfaces (Rodríguez-Caballero et al., 2015). This study used South-African soil, vegetation and biocrusts measurements to simulate the spectral effect of each component on vegetation indices and albedo. In the laboratory simulations of the South-African case study, the effect of biocrusts on albedo was less important than that of the vegetation. However, Rodríguez-Caballero et al. applied this conclusion to cast doubt on the relevance of biocrust cover to the albedo contrast across the Israel-Egypt border, where the ecosystem components (e.g. soil, vegetation, and biocrusts) are different. While aware of the systemic differences, Rodríguez-Caballero et al. suggest the vegetation composition as a possible explanation for the discrepancy between their conclusion and studies that determined that biocrusts are responsible for differences in albedo across the border (e.g. Karnieli and Tsoar, 1995; Burghheimer et al., 2006a; Rozenstein and Karnieli, 2015). Yet, there are a number of other factors not taken into account: In the Israel-Egypt system, the vegetation cover is below the range of 25–75% simulated by Rodríguez-Caballero et al. (Qin et al., 2006; Seifan, 2009; Siegal et al., 2013; Rozenstein et al., 2016), and the soil albedo in the South-African case is considerably lower than that of the bright sands of the Israel-Egypt dunes. Therefore, the combination of sparse vegetation, widespread biocrust cover, and high albedo contrast between the bright sands and the dark biocrusts are the
cause for albedo contrast in the Israel–Egypt dunes, where vegetation plays a minor role in the overall surface albedo in comparison to biocrusts (Karnieli and Tsoar, 1995; Tsoar and Karnieli, 1996). Future studies would benefit from exercising caution when deducing the relative spectral contribution of various components in one ecosystem, based on measurements taken elsewhere. Section 5.1 describes one possible solution to this issue in the form of an indirect approach used for global mapping of cryptogamic cover contribution to biogeochemical cycles (Elbert et al., 2012).

The advancements in remote sensing technology together with sensor availability and reductions in the cost of image products make it easier for scientists to use them in their studies. Lately, studies using high spatial resolution images for the study of biocrusts have started to emerge. Hyperspectral airborne reflective data was used to map the spatial variability and diversity of biocrusts and other cover types in a dune ecosystem (Hill et al., 2008). Very high spatial resolution images taken from a low altitude balloon were used to classify temporal coverage of vegetation, biocrust and sand on a dune with sub-centimeter resolution (Amir et al., 2014). In addition, High spatial resolution spaceborne images, with 2 m resolution from QuickBird and WorldView-2 were used to monitor ecosystem response to drought in small semi-arid watersheds (Paz-Kagan et al., 2014b). The relative affordability of such images facilitates remote sensing monitoring of field experimental plots. However, care must be taken when applying spectral indices for images acquired by different sensors, as bands with similar names may not cover the same spectral range. Therefore, comparing the results of spectral indices applied to images of different sensors may lead to changes in index values that are unrelated to changes in the environment, and result from a difference in spectral band response between different sensors (Li et al., 2013a). High spatial resolution imagery was used to develop an erosion resistance index for desert environments (Hamada and Grippo, 2015). Another study applied reflectance spectroscopy in the field to predict the threshold friction velocity for wind erosion, and this method may eventually be applied from airborne and spaceborne platforms (Li et al., 2015). It could be interesting in the future to try and couple high spectral and spatial resolution optical imagery with high resolution geophysical surveys of subsurface properties, and thus form a connection between above ground biocrusts, and below ground phenomena.

4. TIR spectroscopy

An emittance spectrum depicts the ability of a target to emit thermal energy. Earth surface materials have a peak emittance at about 10 μm. Therefore, the Long Wave Infrared (LWIR) region that extends from 7 to 14 μm is most suited for spectral analysis of these materials. Fundamental vibration modes of various molecular functional groups produce characteristic spectral absorption features that can serve to “fingerprint” many compounds. A significant advantage of proximal and remote sensing in the LWIR is that sensors that operate within this region are not constrained by solar illumination (Salvaggio and Miller, 2001; Eisele et al., 2015). LWIR imagery can be used to penetrate smoke and has been used to measure surface temperature (Collins, 1996). Libraries of TIR spectra currently have a wide range of applications in such diverse fields as chemistry, geology, industrial process control, and forensics (Ribeiro da Luz, 2006).

LWIR remote sensing development has followed a progression toward higher spectral resolution in the drive toward identifying materials based on their emissive spectra (Collins, 1996; Eisele et al., 2015). The Thermal Infrared Multispectral Scanner (TIMS)
(Kahle and Goetz, 1983) and later on the hyperspectral Spatially Enhanced Broadband Array Spectrograph System (SEBASS) were successfully used to map a variety of rocks and minerals (Kirkland et al., 2002; Vaughan et al., 2003; Vaughan et al., 2005). Field and laboratory LWIR spectra of vegetation produced useful information about leaf chemistry and structure (Ribeiro da Luz, 2006). In contrast with VIS to SWIR data, TIR spectral information is more species specific, and the applications are therefore different (Ribeiro da Luz and Crowley, 2007). SEBASS was the first instrument to achieve the necessary data quality for discerning TIR spectral features in plants, and identify a variety of plant species (Ribeiro da Luz and Crowley, 2010). Today, however, LWIR airborne hyperspectral imaging sensors are available from several vendors, including Specim AisaOWL (Holma et al., 2012), Telops HyperCam (Adler-Golden et al., 2014), and Itres TASI-600 (Santini et al., 2014). Therefore, the infrastructure for biocrusts studies from the air using LWIR hyperspectral sensors is readily available. However, the cost of the equipment along with sensor quality issues, and data processing complexity which requires temperature-emissivity separation algorithms for surface emissivity retrieval (Li et al., 2013b), pose limitations on the use of LWIR imagery. These barriers hinder potential end users of LWIR remote sensing technology, and inhibits scientists from integrating this method into their research. Up until recently, biocrust applications using LWIR measurements were limited to surface thermography (Qin et al., 2001, 2002a,b, 2005; Couradeau et al., 2016). Progression in LWIR remote sensing of biocrusts is now up-and-coming, following behind the progression in remote sensing technology, with a certain lag (as will be described in Sections 5.3 and 5.4).

5. Closing the research gaps

In recent years, proximal and remote sensing were used to address several knowledge gaps. These gaps pertain to both the fundamental study of biocrusts, to their function in the ecosystem, as well as to spectroscopy and remote sensing science.

5.1. Role of biocrusts in biogeochemical cycles

The discursive surrounding carbon sequestration usually revolves around ecosystems that produce large quantities of biomass in a short time. However biocrusts are only millimeters thick, and vary in growth rates. Yet the area covered by biocrusts is vast, and therefore their contribution to the global carbon cycle can be significant (Zaady et al., 2000; Evans and Lange, 2001). It was found that the Chlorophyll sensitive NDVI can roughly indicate CO₂ assimilation activity by biocrusts since it is related to the absorbed photosynthetically active radiation, and also represents the biocrusts seasonal photosynthetic activity (Burghheimer et al., 2006a; Burghheimer et al., 2006b). This is in agreement with earlier studies who used field spectra along with coarse spatial resolution remote sensing images to distinguish and detect the biocrusts phenomenological cycle (Schmidt and Karnieli, 2000; Schmidt and Karnieli, 2002; Dall’Olmo and Karnieli, 2002; Karnieli et al., 2002; Karnieli and Dall’Olmo, 2003).

Moreover, Global ecosystem mapping from the Moderate-Resolution Imaging Spectroradiometer (MODIS) (Friedl et al., 2002) was used in the estimation of carbon and nitrogen uptake by cryptogamic covers, a category referring to bryophytes, lichens, and cyanobacteria that also include biocrusts (Elbert et al., 2012). It was found that cryptogams are responsible for 7% of the global terrestrial net primary production, which was claimed by Elbert et al. (2012) to be of the same order of magnitude as the global annual carbon release due to biomass burning and fossil-fuel combustion. Most of this carbon is sequestered in forests, with desert soil and rock responsible for more modest values, but the most intense nitrogen fixation rates are attributed to desert biocrusts. Overall, cryptogams are responsible for almost half of the biological nitrogen fixation (Elbert et al., 2012), and they are a significant source of nitrous oxide and methane emissions (Lenhart et al., 2015) as well as nitric oxide and nitrous acid (Weber et al., 2015).

Since primary production in most ecosystems is nitrogen limited, cryptogams may have a substantial impact on carbon sequestration by terrestrial plants. Accordingly, cryptogams are major players in the global biogeochemical cycles of carbon and nitrogen and should thus be explicitly considered in climate and Earth system models. Since biocrusts are constantly disturbed (Belnap, 1990; Belnap and Eldridge, 2001), it would be interesting to estimate the potential loss in terms of carbon and nitrogen fixation due to persistent disturbances. In addition, it was lately found that climate change results with similar community shifts as that caused by physical disturbance; warming and disturbance resulted in biocrust communities regressing to early successional stages (Ferrenberg et al., 2015). Remote sensing monitoring of those changes could be of use to estimate their impact on biogeochemical cycles. New advances in techniques to characterize biocrusts successional development is presented in Section 5.3. Moreover, it is currently difficult to directly estimate biocrusts by remote sensing means where they are obscured by vegetation canopies and rocks (in the case of endolithic microphyses). The ecosystem mapping approach undertaken by Elbert et al. (2012) is one way to overcome this, which requires generalizing site specific studies to characterize cryptogammic cover across categorical land cover classes. Since ecosystems change over time, and as more knowledge is accumulated through new field studies, the contribution of biocrusts cover needs to be reevaluated and updated to better assess their contribution to global biogeochemical cycles (Weber et al., 2015).

5.2. Monitoring the incentitive establishment of biocrusts

While precipitation and wind have a predominant effect on biocrust cover in Aeolian environments (Amir et al., 2014), studies conducted around the world observed that the presence of fine soil is conducive to biocrust development and recovery from disturbance (e.g. Belnap and Eldridge, 2001; Chamizo et al., 2015). However, in spite of endless speculation by the scientific community regarding the role of fine particles in the incentive development of biocrusts (Concostrina-Zubiri et al., 2013; Fischer and Subbotina, 2014; Doherty et al., 2015), until recently, this subject has not been empirically studied. In an incisive experiment carried out in order to understand the role of sand particle size on filamentous cyanobacteria establishment, the optimum grain size for one strain of Microcoleus vaginitus (a ubiquitous cyanobacterium in many arid lands) was successfully identified (Rozenstein et al., 2014). The rate of biocrust dispersal and its dispersal patterns were examined in a controlled laboratory experiment in which cyanobacterial inoculum was applied to five grain size fractions of sand. Naked eye observations, supported by proximal reflectance spectroscopy, and also by proteins and chlorophyll measurements showed that biocrust establishment was more rapid on the fine sand fractions. However, the latter biophysical measurements exhibited significant experimental noise, as opposed to proximal reflectance spectroscopy, which proved to be more sensitive to biocrust developments, thus enabling the detection of the biocrust signal soon after they establish. Rozenstein et al. (2014) used two spectral indices based on VIS-IR bands to track the biocrusts development (following Zaady et al., 2007), and detected biocrust growth on a sandy substrate at day 32 of the experiment. Re-examination of their experimental data revealed that the attenuation of the SWIR absorption feature of the Calcite substrate by
Biocrusts development can be observed even earlier, at day 14 of the experiment (Fig. 3). Additionally, different modes of dispersal were observed on fine sand, the initial crust development was spatially homogeneous, while on coarse sand, the initial crust development was patchy, restricted and delayed. Complementary analysis of microscopic observations added insight into differences in dispersal modes: in the fine fractions, thin filaments were distributed with low density, while in the coarse fractions thick and dense filaments create a web-like pattern. A new hypothesis was developed based on these development patterns: it was suggested that filamentous cyanobacteria spread easily when the pores between soil grains are small, but as these pores grow larger, the filaments spread is hindered. Therefore, soil porosity is proposed to be an important factor in the development of incipient biocrust. Furthermore, the better establishment of biocrust on fine sand is in agreement with other observational studies in deserts around the world (e.g. Williams et al., 2013; Garcia et al., 2015). These findings have implications for several phenomena, such as sand dune stabilization by biocrusts (Zaady et al., 2014), and formation of vegetation rings (Ravi et al., 2008).

5.3. LWIR spectroscopy for identification and characterization of biocrusts

Biocrusts are often distinct from other cover types in the TIR due to Land-Surface-Temperature (LST) differences. Those differences in LST are caused by differences in albedo and absorbance (Qin et al., 2002a). However, ground emissivity plays an important role in thermal emittance of the ground surface. High resolution TIR proximal and remote sensing (both multispectral and hyperspectral) were already used for soil and higher vegetation applications. However, until recently, only mono (Qin et al., 2001) and dual channel (Dall’Olmo and Karnieli, 2002; Karnieli and Dall’Olmo, 2003) spectral sensors were employed to study biocrusts. It was found that dune sand and biocrusts have slightly different emissivity across a single, wide band (Qin et al., 2005). The drawback of this low spectral resolution is that many materials will appear similar within one or two spectrally wide bands. The spectral features that distinguish one material from another may be very narrow, and may be located in widely dispersed regions of the electromagnetic spectrum. Thus, in order to increase the possibility of detecting these spectral differences, higher spectral resolution was employed in a recent study (Rozenstein and Karnieli, 2015). In this study, high spectral resolution emissivity signatures of sand and biocrust from the northwestern Negev Dunes were used to discriminate biocrust from sand and to rank the biocrusts’ successional maturity. Biocrusts are known to change the top-soil texture throughout their succession, mainly by entrapping airborne dust (Danin and Ganor, 1991; Zaady and Offer, 2010; Williams et al., 2012; Pietrasik et al., 2014). Thus, as biocrusts mature, they contain higher proportions of fine grained particles (silt and clay). The LWIR region is especially useful for the study of quartz sandy environments, since quartz displays a distinct doublet spectral feature in this LWIR, but no characteristic features in the reflective region. Biocrust was found to attenuate this doublet feature, and this attenuation increases with the biocrust successional stage. Thus, as the biocrust is more developed, thicker, and contains more organic matter and fine soil particles, the quartz signal is attenuated. Based on that, a new spectral index was created and applied to multispectral airborne and spaceborne imagery of a dune field intersected by the Israel-Egypt border. This index was found to perform as well as the crust index developed by Karnieli (1997) that is based on VIS-NIR bands for discriminating sand and biocrust. Surprisingly, this new thermal crust index also enhances biocrust signal on loess soil, and not just in the sandy environment for which it was developed (Fig. 4). It would be interesting to examine in the future whether the index can be applied to other environments, where the soil minerals have an absorption feature in that spectral region, for example gypsum soils (Rodriguez-Caballero et al., 2014). In addition, the thermal crust index (Rozenstein and Karnieli, 2015) in combination with the crust index (Karnieli, 1997), and NDVI (Tucker, 1979), was found to be extremely productive for land cover analysis.

The ability to use spectral information to rank biocrusts successional maturity is an important first stage in improving our estimation of carbon and nitrogen fluxes from different ecosystem components (as discussed in Section 5.1 of the paper). Upscaling this ability by using remote sensing imagery to create spatial models of associated ecological functions may be the next natural step. However, since soil moisture affects the same spectral bands used to classify the biocrusts’ developmental stage, it may cripple these applications in cases where soil moisture is spatially heterogeneous or unknown. More research is needed to overcome this fundamental limitation.

Another implication of the increase in biocrust emissivity with their successional development in quartz sand environments relates to measurements of their temperature. It was recently reported that late successional biocrusts that contain the scytomin pigment, which acts as sunscreen and absorbs ultra-violet light, can get up to 10 °C warmer than early successional biocrust (Couradeau et al., 2016). Couradeau et al. show that as a result of this warming, thermosensitive bacterial species in the biocrust are replaced by more thermotolerant forms. This study estimated the biocrust surface temperature using a Fluke IR Thermometer gun (Fluke corporation, Everett, WA, USA) that implicitly assumes a constant emissivity value. Since the emissivity of biocrusts increases with their development, this increase needs to be accounted for.
when estimating their surface temperature even for measurements performed using one wide band that spans across the LWIR. Therefore, it is possible that the difference between different biocrusts as measured by Couradeau et al. is in fact slightly more modest. This does not negate their conclusions regarding a change in the microbial community composition due to temperature differences. On the contrary, the differences in community composition probably contribute to differences in biocrust emissivity.

5.4. Diurnal emissivity dynamics of biocrusts in a sand dune environment

Diurnal changes in soil moisture during the dry season that result from atmospheric water adsorption to the soil surface from the late afternoon throughout the night, followed by evaporation during the day (Agam and Berliner, 2004; Agam and Berliner, 2006) have been linked to diurnal emissivity changes of sandy desert environments (Li et al., 2012; Masiello et al., 2013; Masiello and Serio, 2013; Masiello et al., 2014). Although estimating this variability is essential for many geophysical models, it was only recently explored in the context of biocrusts by Rozenstein et al. (2015b), who explored the variation of diurnal emissivity of bare sand and biocrusts in the northwestern Negev and Sinai Dunes, in Israel and Egypt, respectively. Since the water vapor adsorption process is enhanced with an increase in surface area of soil particles, more water is adsorbed by clay rich topsoil that has more adsorption sites per given soil volume (Agam and Berliner, 2006). While biocrusts contain more clay than bare sand, they also contain structural pores, which effectively increase their surface area (Felde et al., 2014), and thus, increase their adsorption abilities. The higher fines content, along with an increase in the organic component in biocrusts, are responsible for the attenuation of the quartz spectral doublet feature in the 8.25–9.25 μm (Rozenstein and Karnieli, 2015; Rozenstein et al., 2015b). However, the spectral emissivity of dune surfaces is not stable throughout the day, and changes with the topsoil moisture content. Rozenstein et al. (2015b) used high temporal resolution imagery from the Spinning Enhanced Visible and Infrared Imaging Radiometer (SEVIRI) geostationary satellite sensor to monitor these changes across the Israel-Egypt borderline, where different land-use practices by the two countries have resulted in exposed, active sand dunes on the Egyptian side (Sinai), and dunes stabilized by biocrusts on the Israeli side (Negev). They found that the diurnal variations at 8.7 μm in the Negev were significantly larger than in Sinai. They therefore concluded that biocrusts adsorb more water vapors than sand.

This finding advances our understanding of soil-biosphere-atmosphere interactions and of the hydrological cycle in arid environments subject to anthropogenic pressure. In addition, while new evidence suggests that fluorescence cannot serve as a reliable measure of photosynthesis in desert cyanobacteria (Raanan et al., 2015a,b), LWIR measurements may indirectly overcome that restriction, by providing indication of biocrust moisture content, which triggers photosynthetic activity. It remains to be determined whether LWIR spectroscopy is useful in measuring the minimum moisture content at which biocrusts are active. In the future, it would be interesting to examine the role of water vapor adsorption by biocrusts in their metabolic activity. Additionally, future studies should examine water vapor adsorption by biocrusts in other environments, on different soils, where biocrusts composition is varied. Specifically, it would be interesting to examine this for fine grained soils, with a grain size distribution similar to biocrusts, in order to determine if the water vapor adsorption is influenced more by clay content, or the porous structure of biocrusts.

6. Summary and future outlook

Several applications of proximal and remote sensing for the study of biocrusts were reviewed in this paper. To that end, spectroscopy in several regions of the electromagnetic spectrum was employed in the laboratory, in the field from ground observations,
airborne sensing, and finally spaceborne sensing from both polar orbiting and geostationary platforms. Several spectral regions were found to be effective for biocrusts applications. Since each spectral region is sensitive to different features, together they are complimentary.

In addition to organic matter, the fine soil particles integrated into the biocrust affect its spectral signature because of grain size effects, and also changes in the surface mineralogy. Subsequently, both the reflectance and emittance of biocrust change continuously with its succession. Therefore, these spectral changes can be used to monitor the biocrust development. However, in many cases, the spectral effect of moisture needs to be controlled in order to account for successional changes. The trend of spectral change due to biocrust succession is relatively slow to develop compared to spectral changes due to changes in the moisture content occur more quickly, as part of natural wetting and drying cycles. Large wetting events such as rain storms may dry slowly over several days, especially if the sky is cloudy and the surface air temperature is low. Fog and dew precipitation can also increase the topsoil moisture significantly, but the biocrust will usually dry off within a few hours during the day. However even in the absence of these very significant wetting events, in the dry summer, naturally occurring water vapor adsorption to the soil plays a significant role in the diurnal soil moisture cycle, and finally, in the diurnal land surface temperature and emissivity dynamics. The presence of biocrust changes these diurnal dynamics compared to bare soil, as well as the interaction between the topsoil and the atmosphere and the surface mechanical, hydrological and spectral properties.

As we progress into the 21st century, biocrust study is expected to adapt new technologies, and utilize veteran technologies that are becoming cheaper to use and therefore more available for researchers. Recently, studies that use high spatial resolution satellite images (Paz-Kagan et al., 2014b), and even low altitude balloon photography (Amir et al., 2014) to study temporal changes in biocrust cover have started to emerge. It is likely only a matter of time before high spatial resolution imagery from low-altitude remote controlled aerial vehicles will be used for these kinds of studies (Duane Allen, 2010). For over two decades, reflectance spectroscopy was used for biocrust applications, followed by biocrust applications in the thermal region. However, other regions of the electromagnetic spectrum might provide additional information for the study of biocrusts in their desert environment. For example, microwave remote sensing seems to have significant potential in that domain, since it is sensitive to changes in the dielectric constant of the soil and also to the surface roughness (Rozenstein et al., 2016). Therefore, the study of biocrusts might benefit from exploring this avenue in the future.

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References


