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Imaging analysis of biological soil crusts to understand surface heating properties in the Mojave Desert of California

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ABSTRACT

Biological soil crusts (biocrusts) are composed of a combination of cyanobacteria, green algae, lichens, and mosses that can protect arid soil surfaces from erosive forces. The presence of biocrusts in desert regions is influenced by a complex interaction of climatic, edaphic, and topographic variables, but their distribution and coverage densities in southern California deserts are not precisely mapped. Visible satellite bands (red-green-blue; RGB) and infra-red image resolution are generally too coarse to distinguish between biocrusts and their interstitial sand substrates, limiting most remote sensing analysis of these soil biotic assemblages. The purpose of this study was to better understand the relationships between biocrust cover, surface coloration and roughness, and the thermal infra-red (TIR) emission properties of biocrusts to determine if new types of imaging of desert surfaces could be used to more accurately detect biocrust presence. Based on the results from megapixel digital photos and TIR imaging for nearly 130 different, well-developed biocrust surfaces in the Mojave and Lower Colorado Deserts of California, we designed laboratory heating experiments to test the effect of biocrust cover on the heating properties of sandy wash habitats. Biocrust samples collected from the field were subjected to artificial heating and cooling to simulate the Mojave Desert diurnal cycle. We used image segmentation algorithms to separate true-color biocrust images from their sandy substrates, and to map the heating and cooling patterns of these surfaces with different levels of biocrust coloration and roughness. The major findings of this study showed that biocrust patch images in the field had Red texture mean values between digital numbers of 95 and 131 with moderate positive tail shewness levels, indicative of a highly rugose surface of the biocrust cover. Such patches were also well-compacted overall, with moderate skewness toward negative tails. In controlled laboratory temperature experiments to simulate the desert diurnal cycle, surface wetting with a fine mist of water resulted in significantly lower peak surface temperatures of biocrust samples compared to dry biocrust heating results of the same crust and sand samples. The findings of this study can improve future mapping for lichen-dominated biocrust surfaces in the Mojave Desert.

1. Introduction

Cyanobacteria and lichens are major components of biological soil crust communities in deserts of southern California (Rosentreter et al., 2007). Cyanobacteria-dominated crusts are millimeter-thin crusts and are typically invisible to the unaided eye. They provide stability for desert surfaces but are fragile and easily disturbed. Cyanobacteria are unique prokaryote organisms in that they can photosynthesize carbohydrates, as well as fix atmospheric nitrogen into compounds that may enhance soil fertility. Lichen-dominated crusts consist of combinations of cyanobacteria and ascomycete fungi, with occasional algae species as a third bio-component. They are readily visible to the unaided eye, and often have a dark, rugose appearance (Belnap et al., 2001). Lichen-dominated crusts can play a key role maintaining numerous soil properties, including aggregate stability, soil temperature, microbial respiration, and carbon–nitrogen content (Pietrasiak et al., 2014).

Desert biocrusts can improve site productivity by slowing water movement, reducing soil erosion, and facilitating plant community establishment (Belnap, 1995; Belnap et al., 2001). Previous studies have suggested that microfeatures of soil biocrusts can affect infiltration of precipitation and surface runoff on desert landscapes (e.g., Yair, 1990; Eldridge et al., 2000; Williams et al., 2012; Pietrasiak et al., 2014). Increased water availability, plus dust and nutrient capture facilitated by crusts, can enhance desert carbon cycling and soil microbial activity, and may partially offset nutrient disparities between shrub cover and sandy interstitial spaces among biocrust patches (Williams, 2011).

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Potter and Weigand (2016) reported on the application of satellite spectral data to map changes in the distribution of biocrust-favorable habitats across the Lower Colorado Desert of California. The coverage of crust habitat totaled 4841 km^2 in 2014 Landsat images. The proximity of changing areas of biocrust habitat cover to known river flow channels, such as along the Lower McCoy Wash in eastern Riverside County, implied that flash floods associated with heavy precipitation events are important agents that can at least temporarily disturb biocrust habitats by heavy soil deposition.

Nonetheless, large-scale color (red-green-blue; RGB) and infra-red image remote sensing, such as from the Landsat sensor(s) at 30-m ground resolution, is too coarse to distinguish between desert soil biocrusts and their interstitial sand substrates. A spatial resolution of greater than several meters severely limits most satellite image analysis of these ecosystems. Consequently, the distribution and surface reflectance properties of biocrust cover in southern California deserts are not precisely mapped nor accurately quantified at present.

To begin to fill these gaps, new approaches to high-resolution (megapixel) image analysis and thermal infra-red (TIR) imaging for biocrusts in deserts of southern California are described in this paper. The main objective of this investigation was to delineate and characterize desert biocrusts according to the frequency distributions (i.e., histograms) of overall biocrust shape (i.e., relative compactness versus elongation) and surface coloration attributes, and to relate those attributes to surface heating and cooling properties. Building on the results from high-resolution field photo analysis of well-developed biocrust cover sites in the Mojave and Lower Colorado Deserts of California, we also conducted laboratory heating and cooling experiments to better control surface temperature for biocrust and sand substrate imaging. We conducted biocrust surface wetting treatments as part of these laboratory heating experiments.

2. Study areas

Field surveys and biocrust sample collections for this study were carried out in the Mojave and Lower Colorado Deserts of California (Fig. 1). This region is bounded on the west by the Laguna, Santa Rosa and San Jacinto mountain ranges, on the east by the California-Arizona state line, on the north by the transition to the eastern Sierra-Nevada mountains, and on the south by the California-Mexico border (Marks, 1950). Low annual rainfall (50–300 mm) and high temperatures (exceeding 45° C in the summer) make this area one of the most arid in North America.

Five different desert sites in southern California were visited in April and November of 2017 to confirm the presence of lichen-dominated crusts and to collect high-resolution digital images – Boyd Deep Canyon Desert Research Center (BDC) in the Santa Rosa Mountains, the southern McCoy Wash (SMW) in eastern Riverside County, the Sheephole Valley Wilderness Area (SWA) in southern San Bernardino County, the Clipper Mountains Wilderness Area (CMW) and the Mojave National Preserve (MOJA) in eastern San Bernardino County.

3. Methods

3.1. Field imaging of biocrust cover habitats

At each survey site, biocrust-covered areas were located for acquisition of megapixel (3456 × 3456 pixels) digital red-green-blue (RGB) 0.25 m^2 square areas photos with a 4.5–18.0 mm camera lens, spaced at least 5 m apart to facilitate subsequent aerial image pixel classification and validation. True color (RGB) and TIR images of biocrusts within photo areas of the CMW and MOJA sites were also taken using a FLIR Series C2 digital camera. The TIR sensor had a thermal sensitivity < 0.10 °C covering 80 × 60 measurement pixels, at a spectral range of 7.5–14 µm. The FLIR C2 color camera captured RGB images at a resolution of 320 × 240 pixels.

3.2. Laboratory imaging

Eight biocrusts samples were collected and placed into plastic petri dishes from sandy washes of the Sheephole Valley Wilderness Area and the Clipper Mountains Wilderness Area. Samples were returned to the laboratory for heating and cooling experiments. The biocrusts collected included six lichen-dominated crusts, one moss-dominated crust, and one sample that was later confirmed under microscopic examination as a loosely packed soil crust with cyanobacteria present.

Within one week of collection in the field, each biocrust sample was imaged under controlled surface temperature conditions using the FLIR Series C2 digital camera. Petri dishes with biocrusts were placed individually into the center of a pan of smoothed sand substrate and heated at two progressively closer distances (40 cm and 20 cm) to a 250 W artificial light source. Samples were allowed to reach a maximum of roughly 45-50° C surface TIR temperature over two consecutive 15-min heating intervals, and then gradually allowed to cool for two hours to simulate a diurnal cycle in the desert. Biocrust samples were subsequently subjected to the same surface heating and cooling experiments, but with a fine mist spray of water applied just prior to the first heating interval. This additional treatment is relevant to the general effects of rainfall wetting on desert soil surfaces.

3.3. Image processing

Traditional, pixel-based approaches to feature extraction use the reflectance of each pixel to classify imagery. This method typically requires a large number of spectral bands (more than three), limiting the types of imagery that can be used. In contrast, the object based image analysis (OBIA) analysis we implemented for this study used groups of pixels to classify RGB and TIR images based on both the average spectral information from a sub-set of pixels, and on geometric features (such as size, shape, and texture) of objects imaged by the set of pixels. The Example Based Feature Extraction tool in ENVI 5.3 was used for this study (HGS, 2016). The OBIA was initiated by segmentation, which is the process of partitioning an image into objects by grouping neighboring pixels with common values. The segmentation scale could be iteratively adjusted and previewed as many times as needed prior to full image processing. Once optimal segmentation parameters have been established, the OBIA process can be automatically repeated on a collection of images to generate new polygon shapefiles.

For this image analysis, the edge detection segmentation algorithm was set to a scale level of 30 and the full lambda schedule merge algorithm to a level of 75 with a texture kernel size of 19, based principally on the Red band reflectance. Numerous iterations were tested to arrive at these settings for optimal polygon delineation of desert biocrust microfeatures. To isolate the biocrust patches within a photo image, we extracted average polygon Red band values between 60 and 177. This process removed the influence of most background sand, plant material, bright rock surfaces, and dark rock shadow.

Three statistics were computed and compared from the histograms of each OBIA result for biocrust photo images – the Mean, Mode, and Skewness. Mode is the most common value in a data set when the numbers are listed in a histogram in either ascending or descending order, and skewness is a measure of the asymmetry of the distribution of a variable about its mean value. Pearson's first coefficient of skewness is computed from the difference of the mean (or the median) and the mode, divided by the standard deviation (Weisstein, 2016). If the mean is greater than the mode, the distribution will be positively skewed, with a longer tail on the right side of the histogram. The higher the skewness (positive or negative) in a distribution of polygon attribute values, the more diverse the overall image is for that attribute.

COMPACT is an OBIA shape measure that indicates the horizontal compactness level of a polygon. Since a circle is the most compact shape (with a value of 1 / pi), this attribute is computed as: Sqrt (4 ∗ AREA / pi) / outer contour length. COMPACT is thereby the ratio of the area of