REMOTE SENSING OF BIOLOGICAL SOIL CRUST UNDER SIMULATED CLIMATE CHANGE

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ABSTRACT:

Biologic soil crust (BSC) is expected to be sensitive to climate change and disturbance events. We examined the potential for spectral detection of different BSC components at a manipulative experiment at the Mojave Global Change Facility (MGCF) in southwestern Nevada. At the laboratory level, significant spectral differences were present between inorganic soil, cyanobacteria, lichen, and moss from the site. At the field scale BSC types were neither distinguishable nor were there many differences between treatments. Treatments were detectable in high spatial resolution (~4m ground IFOV) airborne hyperspectral imagery using a minimum noise fraction (MNF) analysis, although treatments were not distinct in terms of field-based specific features. There were significant treatment differences between control vs. soil disturbance and lesser but differences in control vs. irrigation treatments, although no differences for nitrogen treatments alone.

1. INTRODUCTION

The largest terrestrial ecosystems are deserts and semiarid ecosystems (barren lands, shrublands and grasslands) which cover more than 40% of the land surface (Millennium Ecosystem Assessment, 2005). These landscapes typically have low ratios of precipitation to evapotranspiration and arid ecosystems have generally low resilience to climate and land use change (Belnap and Eldridge, 2001) and are therefore predicted to be among the most responsive ecosystems to climate change. The Mojave desert in the southwestern U.S. is the driest region in North America. As an ecosystem with a winter dominated precipitation regime, the timing and magnitude of rainfall differentially affects the growth and phenology of shrubs, grasses, and biological soil crusts (BSC). Climate changes will likely lead to altered ecosystem functions. The current climate favors xerophytic shrubs that rely on winter precipitation, however, the northward extension of the North American Monsoon predicted with climate change, will enhance summer rainfall throughout the southwestern U.S., including the Mojave desert and likely favor expansion of grasslands that better utilize summer precipitation.

Biological soil crusts are ubiquitous in arid and semiarid regions as they survive extreme desiccation. These cryptic organisms often comprise a large fraction of the net ecosystem exchange, where they also reduce erosion and provide soil stability, retain soil water, and accumulate nutrients in these low vegetation cover landscapes. BSC are primarily composed of cyanobacteria in drier deserts, e.g., the western Mojave (<100mm precipitation yr^{-1}), as well as lichens and mosses, which dominate under more mesic conditions (200-300mm precipitation yr^{-1}; Burgheimer et al., 2006). BSC is highly susceptible to physical disturbance, elevated CO_2 concentrations, and altered

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precipitation (Belnap and Eldridge, 2001; Evans et al., 2001), thus are likely to be impacted or damaged by climate change and/or intensified land uses like grazing and fuel harvesting.

Because of sensitivity to climate and disturbance, BSC are good indicators of environmental conditions. Thus, monitoring could provide an early indicator of ecosystem change; however, this requires a remote sensing method capable of monitoring the areal extent of arid and semiarid ecosystems for impacts of climate change. Additionally, because summer monsoon storms are intense but localized, relatively frequent repeat observations would be necessary to fully detect their activity over space and time. The low shrub cover characteristic of these system, the significant cover fraction (albeit low biomass) of BSC, and past work supporting spectral characteristics of BSC components (O'Neill, 1994; Karnieli et al., 1999) support the potential to monitor BSC.

We examined the potential to detect BSC and it's response to climate variability and disturbance at a long-term experiment in 2001 at the Nevada Test Site, located about 100 km northwest of Las Vegas, Nevada. The Mojave Global Change Facility (MGCF) experiment was initiated by the U.S. DOE (http://www.unlv.edu/Climate_Change_Research/MGCF/MGCF_index.html) to test the interactive effects of mechanical soil disturbance and increased summer precipitation and nitrogen deposition. NASA flew this site with high spatial resolution data from the Advanced Visible Infrared Imaging Spectrometer (AVIRIS) in the third year of the study. We tested whether MGCF treatments were detectable in hyperspectral data from lab, field and airborne data. We characterized the spectral reflectance of the soil mineral fraction and the dominant lichen, moss, and cyanobacteria components of BSC in the wavelength range 350-2500 nm. Soils of the MGCF are well-drained Aridisols derived from calcareous alluvium (Jordan et al., 1999).

2. MATERIALS AND METHODS

2.1 Site description

The Mojave Global Change Facility (MGCF) is a 0.25 km^2 area in the Nevada Test Site, where grazing and off-road vehicles have been prohibited for over 50 years. It is located approximately 10 km north of Mercury, Nevada, USA (36º 46' 30", 115º 57' 45" and 36º 45' 20", 115º 59' 15"). The dominant shrub species in this Mojave desert ecosystem is the evergreen shrub *Larrea tridentata*, which co-occurs with drought deciduous *Ambrosia dumosa*, and *Lycium andersonii* shrubs, perennial grasses, and forbs (Jordan et al., 1999). Mean annual precipitation at Mercury, NV, averages 144 mm (150 mm 8-yr record at MGCF) with wide year-to-year variance from 32 to 295 mm, most occurring in fall and winter.

The MGCF experiment began in 2001 for eight replicated treatments in a randomized block of 96 14 m x 14 m plots. The experimental treatments we evaluated were: **Control**, with no supplements, **Irrigation** (simulating summer monsoon storms with +75 mm H_2O yr^{-1}), delivered in 3 applications at 3 week intervals in June, July and August. The **High Nitrogen** fertilization (40kg ha^{-1}) is applied as calcium nitrate in the fall (~November). Lastly, **Disturbance** of the BSC was produced by walking/scuffing the exposed soil/crust once a year.

2.2 Biological soil crust and mineral soil composition

The biological soil crust at the MGCF is primarily a rugose cyanobacteria (*Microcoleus vaginatus*) dominated crust (up to 60 % cover) with some lichen and moss colonization. *Microcoleus* secretes long exopolysaccharide sheaths that bind and stabilize the soil for secondary colonization by other cyanobacteria and lichen. Lichen cover is mostly *Collema coccophorum* with some *C. tenax*.

Mosses are uncommon and located under the shrub canopy; *Syntrichia caninervis* is the only common species. The mineral soil samples were treated with 30 % H_2O_2 in an 80 °C water bath to remove the organic fraction, followed by drying at 50 °C for 24 h.

2.3 Laboratory and Field Spectroscopy

Lichen, moss, cyanobacteria, and mineral soil samples were measured in the lab under controlled lighting and viewing geometry with the ASD FieldSpec Pro FR (ASD Inc., Boulder, CO) spectrometer and calibrated using a Spectralon panel (Labsphere Inc., North Sutton, NH). The FOV ranged between 13-27 mm depending on the structure of the crust sample.

In the field, 5 treatment plots were measured per treatment and 5 spectra measured per plot within shrub interspaces. Measurements were made on August 12-13, 2002, ~20 d after the second summer irrigation in the second year of treatment and on July 16, 2003, ~12 d after the first summer irrigation, in the third year of treatment. All plot spectra were measured near solar noon, at nadir, and calibrated to reflectance with Spectralon. The field samples were measured at a fixed height so the samples had a FOV of 0.53 m.

NASA acquired AVIRIS data at 3.4 m pixel resolution on 9 July 2003. Data were georegistered and calibrated to apparent surface reflectance using ACORN (ImSpec LLC, Analytical Imaging and Geophysics LLC, Boulder, CO, USA). Bad bands were removed along with water vapor bands leaving 157 bands which were analyzed using the Minimum Noise Transform (MNF) algorithm in the Environment for Visualization of Images (ENVI, ITT Visual Solutions, Boulder, CO, USA). Of these about 12 transformed bands appeared to contain most of the information content.

3. RESULTS

3.1 Soil composition and spectral features

Soil composition does not account for patchiness of the surface materials (Valko, 2003). Valko (2003) analyzed mineral soil samples collected at the site and showed that mineral composition is dominated by quartz, calcite, dolomite, and feldspars based on X-ray diffraction, confirming that the mineral composition does not have absorption features at the same wavelengths as organic matter. The clay content in the soil is low, the Al-OH absorption at 2200 nm does not overlap the 2080 nm lignin absorption, although the 2350 nm carbonate absorption is strong and overlaps the BSC starch absorption at 2310 nm.

To determine whether the BSC have unique spectral signatures that are different than soil, we measured BSC endmembers from field samples in the lab, shown in Fig. 1. Spectra are uncorrected for ASD detector offsets but water bands were removed. The moss endmember is the only one with strong chlorophyll and red-edge features. Lichen has a small pigment absorption and the lowest NIR reflectance. Both soil and cyanobacteria have their greatest difference from moss and lichen in the 1800 to 2250 nm water, lignin and clay region. In contrast to moss and lichen, the cyanobacteria and soil spectra show increasing reflectance across the visible, with a concave shape in the blue to green region that is characteristic of organic matter, and are more linear from there into the 1800 nm SWIR region. BSC absorptions at 1720, 2080 and 2310 nm are consistent with organic matter absorptions identified by Karnieli et al. (2001).

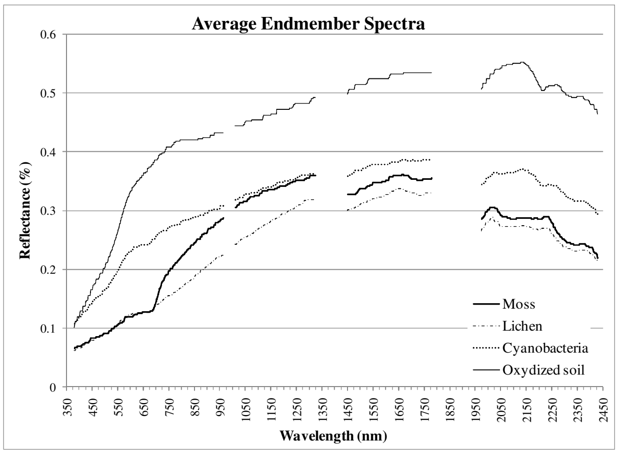

Figure 1. Mean laboratory measured BSC endmember spectra of oxidized soil, cyanobacteria, lichen, and moss.

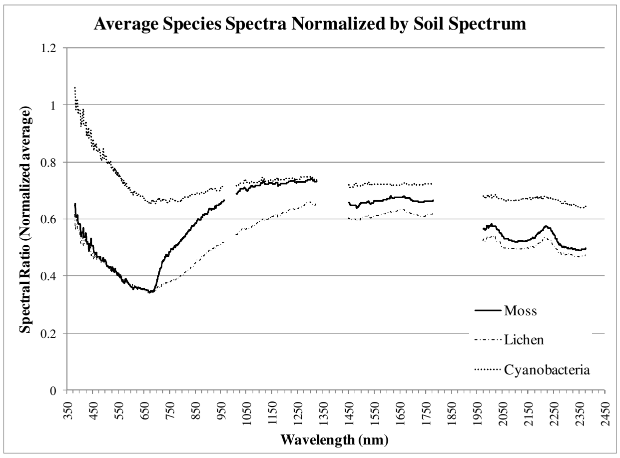

Figure 2. Ratio of BSC endmembers to oxidized soil from laboratory measurements shown in Fig. 1.

The cyanobacteria and lichen are more similar to each other in shape between 780 -1400 nm than to moss, although all BSC and soil have similar reflectance across the 1400 to 1750 nm region. Moss and lichen have two broad absorptions that are not present in soil and cyanobacteria between 2000 and 2250 nm, and 2250 and 2350 nm. To more easily compare the spectral shapes, Fig. 2 shows the mean BSC endmembers ratioed to the mean oxidized soil spectrum. All BSC are darker across the spectrum than soil (which would be 1.0), and are darkest in the visible spectrum. The red-edge in the moss is clearly present and is most distinctively different from lichen and cyanobacteria in the NIR. Although all BSC have the general concave shape between 380 and 680 nm characteristic of organic matter, but differ markedly from soil. All BSC are similar in the 1400 to 1800 nm region and do not differ from soil in shape but only in albedo. Lichen and moss show strong absorption differences from soil in the SWIR, with two absorption features in the 2000-2400 nm range.

3.2 Field soil and BSC reflectance

Treatments were averaged and reflectance is shown in Fig. 3 for Control, Disturbance, Irrigation, High Nitrogen, and Irrigation plus High Nitrogen. The most striking observation is how similar the spectra of the treatments are in this dataset. This seems largely attributed to the data being collected in the 4th and 5th year of a regional drought and because the irrigation treatment had sufficient time to dry before the field observations were made. All field spectra expressed the broad organic matter absorption across the visible region and monotonically increasing reflectance to 1800 nm. The disturbance treatment, which largely removed the BSC and exposed the soil, had the same spectral features as the oxidized soil in the lab. The control treatment expresses a small absorption in the SWIR range that is more like the lab BSC in shape. In the nitrogen treatment without irrigation, it appears that the BSC is unable to use the additional nitrogen under these dry conditions, as the spectra continue to look most like the control. Lastly, cyanobacteria have some absorption bands shared with other BSC in the SWIR but are of intermediate strength in the 2000 - 2400 nm region.

Ratios of the mean treatments to the mean control demonstrate the much higher albedo of the disturbance treatment across all wavelengths (Fig. 4). The other treatments have higher reflectance than control in the visible and NIR, consistent with lower photosynthetic pigment concentrations, although in the NIR (~1300 nm) there are few treatment differences. The irrigation treatments had higher reflectance across the visible and lowest reflectance in the NIR and SWIR, possibly indicating higher water content.

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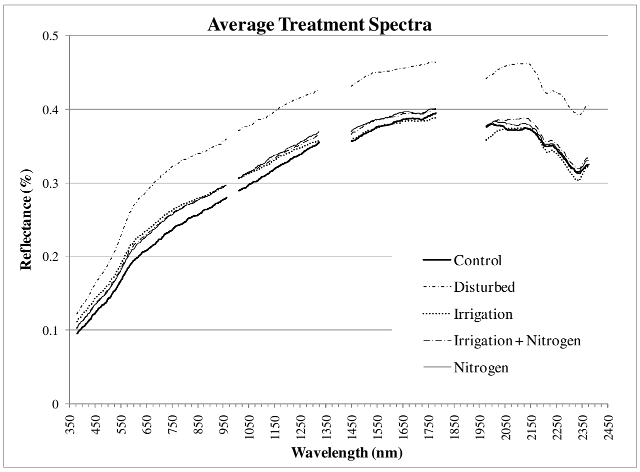

Figure 3. Mean spectra of MGCF treatments for control, irrigation, high nitrogen, irrigation plus nitrogen and disturbance.

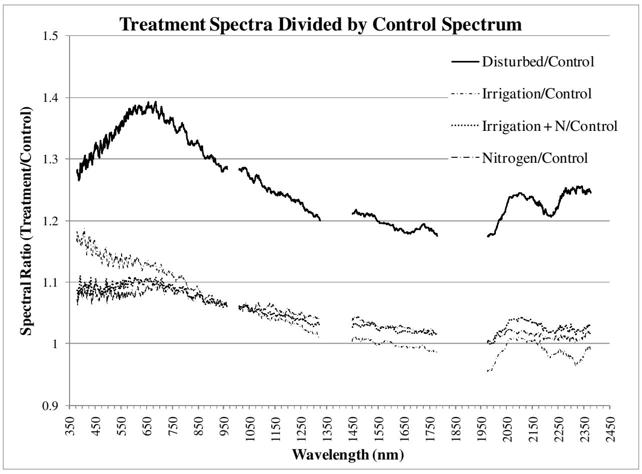

Figure 4. Mean treatment spectra divided by control spectrum for treatments in Fig. 3.

The AVIRIS results for the MGCF treatments show the impact of soil disturbance in the false color infrared image (Fig. 5a). Figure 5b shows a composite of the three Minimum Noise Fraction bands (MNF bands 4, 5, 9 as RGB) that show the most treatment related differences. The apparent differences among plots are attributed to a loss of the BSC at this stage in the long-term treatments.

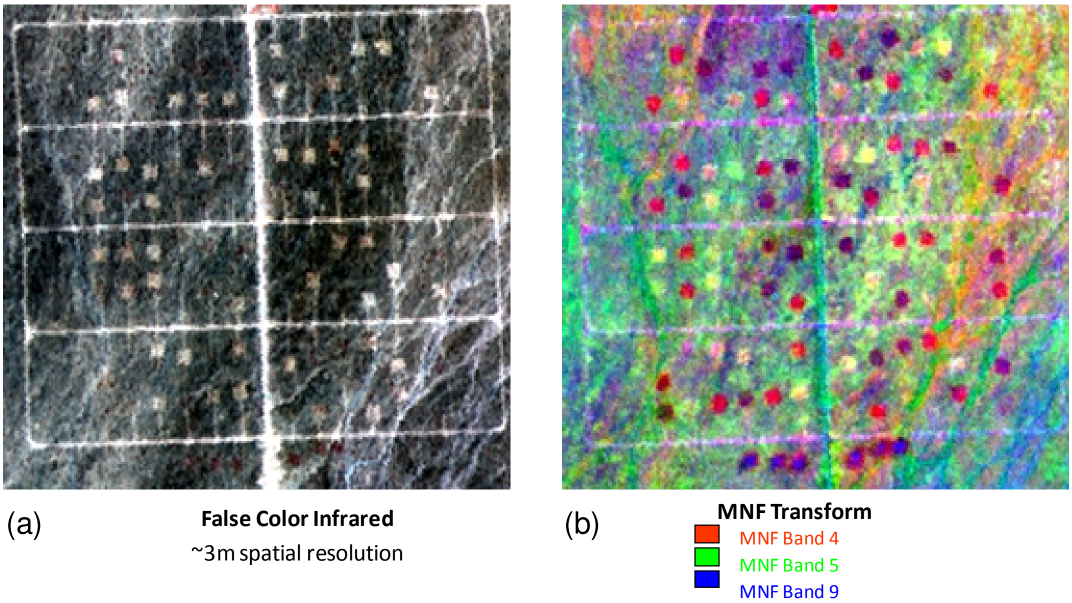

Figure 5. a) 9 July 2003 AVIRIS image in false color infrared image. b) Minimum Noise Fraction bands (MNF bands 4, 5, 9 as RGB) exhibits some correlation to treatment plot locations.

In some locations irrigation treatments are evident but over the entire area, treatments differ by combinations rather than as single treatment effects. Thus, all disturbance treatments stand out as do some irrigation combination treatments.

4. CONCLUSIONS

We examined laboratory and field measured reflectance spectra and high spatial resolution airborne hyperspectral data of experimental treatments for soil disturbance, irrigation, simulating increased

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summer rainfall, and nitrogen additions, simulating dry nitrogen deposition. Laboratory spectra of lichens, cyanobacteria, mosses, and bare soil were measured under controlled laboratory conditions and shown to be spectrally distinct over much of the visible and infrared spectrum. At the field scale, spectra were more similar in overall shape in each of the MGCF treatments and individual BSC could not be distinguished. The field spectra most closely resemble cyanobacteria from laboratory measurements, which are known to cover up to 60% of the inter-shrub spaces. The pattern appears consistent with this BSC functional type. There were however, significant treatment differences between control, soil disturbance, and irrigation treatments in field spectral measurements. The changes appear consistent with loss of cyanobacterial crust but Ustin et al. (2009) showed lichen also decreased.

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