Applying a field spectroscopy technique for assessing successional trends of biological soil crusts in a semi-arid environment

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Abstract

We studied the successional stages of biological soil crusts (BSCs) by using in-situ spectroscopic techniques during 6 years of recovery following scraping-sterilization and scraping-crumbling disturbances on north- and south-facing slopes and in plots with and without overland water runoff barriers. Two spectral indices, the Brightness Index (BI) and the Normalized Difference Vegetation Index (NDVI), were used as indicators for evaluating BSC succession, with special attention to differences between the north- and the south-facing slopes. We found that BSC succession could be expressed as linear regressions of the above-mentioned indicators during the experimental years for the different treatments. Both indicators were found to be significantly different in each of the experimental years: BI values decreased while NDVI values increased for each of the three treatments. Thus, the BI can serve as a good indicator during the early years following disturbance while the NDVI can be useful after crusts have become established. We conclude that spectral reflectance measurements of BSCs can be a useful monitoring technique for studying the regeneration of the soil surface without direct disturbance.

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Keywords: Biological soil crust; Brightness index; NDVI; Reflectance; Runoff; Spectroscopy; Succession; Watershed

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1. Introduction

Soil crust formation is a common and widespread phenomenon in arid and semi-arid soils. Distinction should be made between physical and biogenic crust formations. A physical crust is defined either as one formed by a combination of raindrop impact on the soil surface along with physiochemical dispersion of soil clay, or as one formed by the sedimentation of fine material as turbid water infiltrates following overland flow (Singer, 1991). Physical crusts can be found in areas that contain high amounts of coarse sandy soils, low organic matter and high sodium (Belnap et al., 1999). They are characterized by low soil stability and soil aggregates, which are easily broken down under the impact of water.

Biological soil crusts (BSCs), in contrast with physical crusts, can be found in semi-arid and arid regions in places where landscapes are undisturbed by anthropogenic activities (Evenari, 1985; Friedman and Galun, 1974; Skujins, 1984). They can also be found in pristine areas, heavily disturbed by off-road vehicles, chemicals, and pollution (West, 1990). The BSC community varies significantly in precipitation regime (Johansen, 1993). The BSC cover is characterized by a tightly structured surface typically varying in the Negev Desert from a 2-mm thick, relatively homogeneous cyanobacterial crust, to a complex 15-mm thick crust composed of communities of mosses, lichens, soil algae, fungi, and cyanobacteria (Zaady et al., 1997).

BSCs play an important role in the desert ecosystem. Past studies of BSCs have been based on surveys of communities, their morphology and species composition, geographical distribution, nutrient cycling, soil stabilization, and changes after disturbances such as grazing, fires, and desert storms (Belnap, 1995; Belnap and Lange, 2001). The microphytic community of BSCs, composed of cyanobacteria and soil algae, secretes mucilaginous polysaccharide sheaths that bind the soil particles (Bailey et al., 1973; Bertocchi et al., 1990; De-Philipis et al., 1993). Consequently, they play an important role in stabilizing soil against wind and water erosion (Belnap and Gillette, 1997; Eldridge et al., 2002; Gillette and Dobrowalski, 1993).

The effect of BSC composition on soil–water relations is highly variable among different regions, soils, and climatic regimes. Soil structure and texture and rainfall amount and duration may, in turn, affect the development of BSCs and their composition. These factors, combined with the roughness of the soil surface, can ultimately influence the hydraulic cycles at a given site. In the loessial soils (Belnap and Gillette, 1998; Warren, 2001, pp. 349–360) of the Negev Desert, the combination of relatively high silt and clay particle content and the cyanobacterial exudates change the soil–water regime by affecting runoff, rain interception, water-holding capacity, and soil moisture content (Eldridge et al., 2002; Shachak et al., 1998; Yair, 1990; Zombre et al., 1996). Eldridge et al. (2000, 2002) showed in the northern Negev desert of Israel that scraping off the crust increased infiltration, whether the soil was sandy or loessial. Danin et al. (1989) showed the role of BSCs in increasing the percentage of organic matter, silt, and clay in the soil of sand dunes, subsequently contributing to their stabilization. In addition, BSCs have significant ecological roles in the fixation of carbon and nitrogen and serve as primary producers in dry ecosystems (Burgheimer et al., 2006a, b). They have a major effect on vascular plants (delayed or enhanced germination) and on soil characteristics (nutrient cycling, water regime, nitrogen fixation, and organic matter content) (Belnap and Lange, 2001; Zaady et al., 1997, 1998). Human-induced disturbances (e.g., livestock trampling, driving of
off-road vehicles, mining, etc.) cause damage to crusted soil surfaces, allowing erosive forces to operate, leading to soil degradation and desertification (Belnap, 1995).

Lange et al. (1992) reported that the first colonizers of the sand dunes of the northeastern Negev desert were filamentous cyanobacteria, while Zaady et al. (2000) reported that green algae and mosses appear later in the succession process in places in the northern Negev Desert, where the water regime exceeds 250 mm yr\(^{-1}\), and that presence of soil lichens was indicative of a fully developed crust. These findings have been supported by other studies (Johansen, 1993; West, 1990). Nevertheless, limited availability of resources, such as water, time, and space, may stop the successional stage at a certain state (Pickett and McDonnell, 1989). The ability of the filamentous cyanobacteria (e.g., *Microcoleus* sp.) to colonize new areas, where plant cover is restricted, landwater is scarce, and harsh microenvironmental conditions prevail, is due to their ability to withstand dehydration. *Microcoleus* sp. move in response to wetting or drying events by migrating to the soil surface or retreating to their refuge below (Belnap and Gardner, 1993; Buzer et al., 1985; Danin, 1978; Garcia-Pichel and Pringault, 2001).

Physical effects (soil structure, radiation intensity) and topographic traits (elevation, slope, and aspect) that affect water availability and soil moisture, also influence the BSC community and the successional pathways. When physical conditions are similar, disturbances are the key factors that determine a specific successional stage (Zaady et al., 2000). Typical BSC-succession studies have measured percentage of crust cover (Kleiner, 1983) and phytomass of algae and lichens (Orshan and Zohary, 1985) or they have quantified chlorophyll, polysaccharide, and protein content (Zaady and Bouskila, 2002). These traditional BSC-monitoring methods involve disturbing the soil surface by removing the crust for laboratory analyses. They also entail greater expenditure of time and money to conduct than do remote sensing techniques. In addition, BSCs often have very high spatial variability, even on a microscale, thus increasing the cost of traditional methods to achieve statistical reliability.

Remote sensing techniques have been applied to various studies of BSCs. O’Neill (1994), Karnieli and Tsoar (1995) and Karnieli et al. (1996) tested the feasibility of applying this technique to the photosynthetic activity of the BSCs that cover most of the soil surfaces in the semi-arid regions of Australia and Israel, and of many other deserts of the world (West, 1990). These studies demonstrate that reflectance of lower plant communities can be detected on a variety of soils.

Temporal and spatial variations of vegetation and soil conditions can be monitored from satellite remote sensing images by utilizing spectral indicators, usually based on more than one spectral band (e.g., Lambin, 1999). Escadafal and Bacha (1996) developed the Brightness Index (BI), which applies the reflectance values in two visible bands, green (G, 500–600 nm) and red (R, 600–700 nm) and one near-infrared band (NIR, 700–1100 nm), to calculate the brightness of a surface:

\[
BI = \sqrt{G^2 + R^2 + NIR^2}. \tag{1}
\]

This index is suggested in the current research as an indicator for desertification/rehabilitation processes, since darker soils are indicative of a greater presence of cyanobacteria (Karnieli and Tsoar, 1995).

Vegetation indices (VIs) (Bannari et al., 1995) have been developed during recent decades, based on different combinations of the ratio between the R band, which
corresponds to the region of maximum chlorophyll absorption, and the NIR band, which corresponds to maximum reflectance of incident light by living vegetation. The most widely used index is the Normalized Difference Vegetation Index (NDVI) defined as

$$\text{NDVI} = \frac{\text{NIR} - \text{R}}{\text{NIR} + \text{R}},$$

where \( \text{R} \) and \( \text{NIR} \) are the radiances and reflectances, or at least ‘apparent reflectances’ in the R and the NIR spectral bands, respectively (Rouse et al., 1974). The NDVI values lie in the range \(-1.0\) to \(+1.0\), denser and/or healthier vegetation having higher positive values.

The NDVI is well correlated with various vegetation parameters, such as green biomass (Tucker, 1979), chlorophyll concentration (Buschmann and Nagel, 1993), leaf area index (Asrar et al., 1984), foliar loss and damage (Vogelmann, 1990), photosynthetic activity (Sellers, 1985), carbon fluxes, and phenology (Justice et al., 1985). It has also been found to be useful for various image analyses like crop classification, green coverage, and change detection. Karnieli and Tsoar (1995) and Karnieli et al. (1996) tested whether the high NDVI values may be caused by the photosynthetic activity of BSCs, which cover most of the soil surfaces in the semi-arid regions of the Negev desert. They found that the spectral reflectance curves of lower plants can be similar to those of higher ones and their derived NDVI values can be as high as 0.30 units. A high correlation \((r = 0.79)\) was reported between NDVI values and chlorophyll content of a wet BSC (Karnieli et al., 2001, pp 431–455). O’Neill (1994) studied the reflectance spectra of BSCs in semi-arid regions of Australia on a variety of soils. Noticeable differences upon wetting of the BSCs were observed using this method. The large percentage cover of BSCs and litter in ungrazed semi-arid rangelands was noted. Consequently, it is assumed that a Vegetation Index, such as NDVI, can serve as a second indicator for recovery of BSCs.

There are many VIs that can be applied. Testing all/most of them is far beyond the scope of the current research. The reason for choosing these two stems mainly from their original purpose. The BI groups soil indices and the NDVI represents the group of vegetation spectral indices. This choice lines up well with the characteristics of the BSCs that compose of both vegetation and soil.

Following the findings discussed above, we hypothesized that successional trends of BSC cover can be monitored by measuring the spectral reflectance of the microphytes. The aim of this long-term study was to demonstrate the ability to monitor successional trends of BSCs using a quick and easy technique, namely \textit{in-situ} spectroscopy. Hundreds of samples can be read in a relatively short time (0.5 min per sample). For this purpose, we measured the spectral reflectances of the BSCs during 6 years of recovery after disturbance, under field conditions, in a semi-arid watershed in the Northern Negev (Israel).

2. Methods and materials

2.1. Study area

The research site is located at the Sayeret Shaked International Long-Term Ecological Research station (Gosz et al., 2000) near Beer-Sheva in the northern Negev of Israel \((31°17'N, 34°37'E)\). The site is a hilly watershed that has been closed to livestock grazing since 1987. Aerial photography of an area located a few kilometers from the study site clearly reveals a distinguishable difference in contrast between the darker tones within a
fenced-off area and the lighter tones of the grazed area beyond the fences (Appendix A, in electronic version). A closer view of the area reveals distinct patches of shrubs on a BSC matrix, characteristic of the spatial heterogeneity of the landscape (Shachak et al., 1998). The dominant shrubs in these scattered patches are *Noaea mucronata* (Chenopdiaceae) and *Atractylis serratuloides* (Compositae) (Feinbrun-Dothan and Danin, 1991; Zaady et al., 1996). About 75% of the soil surface between the shrubs is covered by BSCs composed of cyanobacteria with scattered mosses on the south-facing slopes (about 10 mm thick), and by BSCs consisting of cyanobacteria, algae, and dense moss and lichens on the north-facing slopes (about 15 mm thick) (Zaady et al., 1998). Rainfall at the study site, occurring only during the winter months, has a long-term annual average of 200 mm. The 200 mm isohyet is considered to form the transition zone between arid and semi-arid deserts in Israel (Zaady et al., 1996). The soil is loess, 1 m thick, with 14% clay, 27% silt, and 59% sand (USA classification: loess soil with sandy loam texture—Calciixerollic, Xerochrepts (Dan et al., 1977)) on Eocene bedrock (Zaady et al., 2000). The salt content of the upper 25 cm soil layer is low, with an electroconductivity of 0.04 dS m\(^{-1}\).

Zaady et al. (2000) studied crust components at the study site of Sayeret Shaked Park. The most common moss in the area is *Aloina bifrons* (Pottiaceae), while the second most common species is *Crossidium crossinerve* var. *laevipillum* (Pottiaceae). The first species is dominant in the south-facing slope and the second predominates the north-facing slope. Both species are adapted to arid climates. They also studied the cyanobacteria group, which includes two dominant species: *Microcoleus vaginatus* (Chroococcales), a filamentous cyanobacterium that grows 0–2 mm below the soil surface, and *Nostoc punctiforme* (Oscillatoriales) that grows on the soil surface. Other species present in low numbers are *Chroococcus tugidus*, *Calothrix* sp. (Oscillatoriales) and the green algae *Palmella* sp. (Tetraspoales) (Zaady et al., 2000).

### 2.2. Field work

Forty-eight plots (40 × 40 cm\(^{2}\)) were laid out on the south- and north-facing slopes (24 plots on each slope) of a watershed at the Sayeret Shaked Park in 1994. The topsoil was scraped off of 32 of these plots (16 per slope) to a depth of 2 cm. Two BSC recovery processes were monitored following either of two treatments: (1) 16 plots per slope were refilled with local scraped and sterilized soil (scraped-sterilized treatment) and (2) 16 plots per slope were refilled with crumbled aggregates of local scraped crust (scraped-crumbled treatment). The last treatment (3) included the 16 remaining undisturbed plots (eight per slope) served as controls. Twelve plots on each slope (four for each treatment and four control plots) were enclosed within plastic barriers protruding 5 cm above and extending 5 cm below the soil surface to minimize the intrusion of water from surface runoff and rain spatter (Appendix B, in electronic version). These plots were referred to as ‘closed plots’. The boundaries of the other 12 plots were marked with wire to allow surface runoff water to enter/pass through the plots (Appendix B, in electronic version); hence they were referred to as ‘open plots’. Photographs taken in December 1993 (Appendix B, B, in electronic version) show that only bare soil was present within the experimental plots a year before the spectral measurements commenced, while the soil surface outside the plots was characterized by a dense cover of microphytes.
2.3. Soil and crust samples for moss stem (caulidia) density and chlorophyll content

Soil and crust samples from the plots were collected from the north-facing slope at the beginning and end of the study in 1995 and 1998 (for evaluation of their chlorophyll content). We followed the suggestions of Johansen (1993) and West (1990) and evaluated crust development by determining the density of moss stems (the stem with leaf-like structures) and chlorophyll content. Crust samples were moistened and incubated under sunlight for 1 h to count the moss stems. The chlorophyll in these samples was extracted in an 80% acetone solution (see Lichtenthaler and Wellburn, 1983) then quantified analytically for total chlorophyll, chlorophyll \( a \) and chlorophyll \( b \) content with a spectrophotometer, based on the Beer–Lambert Law and the extinction coefficient for chlorophyll.

2.4. Spectral reflectance measurements

The spectral characteristics of the surface reflectance of the BSC was studied \textit{in situ} in the field. We used a Li-Cor LI-1800 field-portable spectrometer with fixed 2 nm spectral resolution wavelength increments between 400 and 1100 nm and a 15° field of view. It was hand held about 1 m vertically above the plane of the surface of the ground being measured. Note that all measurements were taken during the wet season—in the northern Negev Desert the rainy season, from November to March, follows a long dry spell—when the microphytes were wet and active, which is evident from the ground cover outside the study plots (in seen in Appendix B, in electronic version). By wet season, we refer to a period when soil moisture is 10–22% of the soil capacity, allowing the crusts to be active (Burgheimer et al., 2006a, b; Karnieli, 2003). The reflectance was calculated by relating the target radiances to the downwelling irradiation, as measured by a cosine receptor. Four reflectance spectra replicates from a single site were averaged to reduce measurement noise. In addition, field measurements with the Licor-1800 spectrometer suffer from random noise in the blue and NIR portions of the spectra. This noise was removed, e.g., the spectrum was smoothed, with a median filter consisting of a moving window of five points. The reflectance in the green, red, and NIR spectral regions was determined by averaging the reflectance values within the 500–600, 600–700, and 700–800 nm regions, respectively. The \( \text{BI} \) and the \( \text{NDVI} \) values of each spectrum were calculated from Eqs. (1) and (2). Measurements were taken during a 6-year period from 1994 to 1999.

2.5. Statistical analysis

Data were processed using analysis of variance with the SuperANOVA statistical package. One-way ANOVA, with Duncan Multiple Range Tests (Sokal and Rohlf, 1995) were used to test the differences in the slope directions, treatments (control, scraped-sterilized, and scraped-crumbled), and closed plots vs. open plots during the experimental years as independent variables. The dependent variables were either \( \text{BI} \) or \( \text{NDVI} \). Furthermore, we used one-way ANOVA, with the same tests, to test differences in parameter means between the moss density at the beginning and the end of the study. Differences were considered statistically significant if \( p < 0.05 \). The correlation coefficients were calculated for the \( \text{BI} \) and \( \text{NDVI} \) for each of the treatments tested and the regression curve was drawn.
3. Results

The averaged spectra (Fig. 1a–f) for the different treatments (scraped-sterilized, scraped-crumbled and control), for each year (1994 to 1999), and for the different slope aspects (north and south), all have a typical soil-curve shape: relatively low in the blue region (400–500 nm), increasing gradually towards the NIR region (700–1100 nm). The level of reflectance corresponds to the brightness of the soil: the higher the level of reflectance the brighter the soil. The level of reflectance decreases along the observation years in all treatments, particularly in the 600–800 nm ranges (Fig. 1a–f), with the highest reflectance level in 1994 and the lowest in 1999. In addition, each treatment had a higher level of

Fig. 1. Yearly dynamics of the BSC spectra for the different treatments and different slope orientations.
reflectance on the south-facing slope than its corresponding treatment on the north-facing slope. The values of the BI and the NDVI are presented in Table 1. It should be noted that the BI values range from 70.82 to 6.82, generally decreasing during the study years. In most cases, higher BI values are observed on the south-facing slope. The NDVI values range from 0.01 to 0.11, generally increasing with time. Higher NDVI values usually represent the north-facing slope.

The BSCs are expressed as linear regressions of the above-mentioned indicators during the measuring years for the different treatments, with special attention to the difference between the north- and south-facing slopes. There was a strong correlation between each indicator and the time scale (Fig. 2a and b). Since the north-facing slopes are exposed to less direct solar radiation, soils on these slopes have more water availability and soil moisture (Boeken and Shachak, 1994) and eventually, these conditions influence the soil crust community and the successional trends (Zaady et al., 2000). Both indicators were found to be significantly different \((p<0.001)\) in each of the experimental years. Decreasing BI values and an increase in NDVI values were observed for each of the three treatments, along the experimental years \((p<0.001)\). Comparison among the three treatments reveals that the NDVI values for the control were higher than those for the scraped-crumbled and the scraped-sterilized treatments \((p<0.01)\) (Fig. 2c and d). Lower NDVI values were obtained during the years from scraped-sterilized plots (Fig. 2d). Such differentiation cannot be observed in the BI values (Fig. 2c). Although significant trends were observed for the indicators in plots with and without barriers \((p<0.001)\) over the duration of the experiment, no significant differences were found between them during each year of the test (Fig. 2e and f).

### Table 1

<table>
<thead>
<tr>
<th></th>
<th>Scrape-sterilized</th>
<th>Scrape-crumbled</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North</td>
<td>South</td>
<td>North</td>
</tr>
<tr>
<td><strong>BI</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>57.29</td>
<td>70.82</td>
<td>56.79</td>
</tr>
<tr>
<td>1995</td>
<td>40.27</td>
<td>N/A</td>
<td>27.81</td>
</tr>
<tr>
<td>1996</td>
<td>41.43</td>
<td>50.83</td>
<td>36.97</td>
</tr>
<tr>
<td>1997</td>
<td>23.58</td>
<td>N/A</td>
<td>29.38</td>
</tr>
<tr>
<td>1999</td>
<td>7.74</td>
<td>14.65</td>
<td>9.73</td>
</tr>
<tr>
<td><strong>NDVI</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>1995</td>
<td>0.03</td>
<td>N/A</td>
<td>0.04</td>
</tr>
<tr>
<td>1996</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>1997</td>
<td>0.03</td>
<td>N/A</td>
<td>0.03</td>
</tr>
<tr>
<td>1998</td>
<td>0.09</td>
<td>0.08</td>
<td>0.09</td>
</tr>
<tr>
<td>1999</td>
<td>0.11</td>
<td>0.07</td>
<td>0.11</td>
</tr>
</tbody>
</table>

N/A = data not available.
A logarithmic model of the relationships between the two recovery indicators reveals a strong correlation ($R^2 = 0.85$) (Fig. 3). Different marks were assigned for each sampling year. It can be seen that during the earlier years (1994–1996) of measuring, BI varied more significantly, thus better describing the temporal dynamics, while these changes were more pronounced in the NDVI readings taken during the later years (1997–1999).

Fig. 2. Trends of the spectral indicators along the study period in the north- and south-facing slopes of the watershed ($p < 0.001$): (a) Brightness Index (BI); (b) Normalized Difference Vegetation Index (NDVI), indicators along the study period in the different treatment plots ($p < 0.001$), (c) BI; (d) NDVI, and along the study period in the plots with barriers (closed) and without (open) ($p < 0.001$), (e) BI; (f) NDVI.

A logarithmic model of the relationships between the two recovery indicators reveals a strong correlation ($R^2 = 0.85$) (Fig. 3). Different marks were assigned for each sampling year. It can be seen that during the earlier years (1994–1996) of measuring, BI varied more significantly, thus better describing the temporal dynamics, while these changes were more pronounced in the NDVI readings taken during the later years (1997–1999).
4. Discussion

Successional growth of BSCs can be affected by physical components (soil structures and types, radiation intensity) and by topographic attributes (slope aspects affecting water availability and soil moisture) (Belnap, 1995; Belnap and Gillette, 1997; Lange et al., 1997). Disturbances that damage the local soil surface force the succession processes to recommence from the level of the disturbance (Pickett et al., 1987). The proposed method, using a portable spectrometer, proved to be an efficient tool for the current objectives since it was able to rapidly measure the temporal and spatial dynamics of BSCs without disturbing the surface. The data sets obtained in the course of this study showed a substantial decrease in the BI values and an increase in NDVI values during the experimental years, from the time of the disturbances. It had been assumed that succession of BSCs would be expressed by their soil color: the more developed the microphytic community, the darker the soil. However, all correlations between the BI and the timescale were relatively low, whereas the NDVI showed relatively higher correlation values. Thus, NDVI was found to be a better indicator for the succession dynamics of the soil surface. As with the BI, the NDVI is also known to be sensitive to dark soils (Huete et al., 1985). Since the spectra were sampled during the wet season when the microphytes were active, the NDVI was the more dominant indicator. It is important to note that rainfall events, runoff, and field capacity moisture levels are quite common in our research area (Zaady et al., 1996). For example, in 1994, rainfall events of 22, 18.5, 16.5, 44, 11, and 24 mm occurred respectively at our site on 2, 6, 15, 23, 26, and 29 November. Fließbach et al. (1994) reported soil moisture conditions near field capacity at a lower-rainfall site than ours in the Negev for a period of nearly 3 months in 1992. Presumably, if the same measurements were to be carried out during the dry season, the NDVI would not reveal such high correlations. Nevertheless, from Fig. 3 it can be concluded that the BI can serve

![Fig. 3. Relationships between the two recovery indicators, BI and NDVI. Different marks were assigned for each sampling year.](image)

\[
BI = -19.714 \ln(NDVI) - 29.566 \\
R^2 = 0.8537
\]
as a good indicator during the early years after disturbance, when relatively few microphytes are established in the soil surface. Later, when the BSCs become thicker and contain more biomass, the NDVI is a better indicator.

Filling the scraped plots with sterilized soil should have eliminated all the organisms that were in the plots (Tables 2 and 3). Re-colonization of these plots by microphytes, either by wind or by surface runoff water, initiated the successional process. The difference in chlorophyll content from the three treatments in 1995 vs. their corresponding treatments in 1998 is an indicator for microphytic activity, i.e., an indicator for the change in the successional age (Table 3) (Belnap and Lange, 2001; Johansen, 1993; Lange et al., 1992). The second treatment, which entailed filling the scraped plots with crumbled crust aggregates, was actually re-inoculation of the plots by crust aggregates. The substantial increase in NDVI values calculated from reflectance showed that all the areas covered with BSCs were undergoing successional processes. The results indicate that the area had not fully recovered from the heavy grazing disturbances that were prevalent before the watershed was fenced off in 1987. The microphytes, including mosses, are still following successional pathways and have not reached their highest level of development (Tables 2 and 3). Comparing NDVI levels among the three treatments, the spectral reflectance measured from the scraped-sterilized treatment lags 1 year in development behind the control and about half a year behind the scraped-crumbled treatment (Fig. 2d).

Constructing plastic barriers around the plots did not produce significant differences in the successional rate trends. One would expect that these barriers would decrease the number of microphyte colonization propagules carried to the plots by runoff water. The only propagules that should colonize are those carried by wind with dry deposition (Danin

Table 2
Density of moss stems (cm$^{-2}$) in the three treatments: scraped-crumbled, scraped-sterilized, and control plots in the north- and the south-facing slopes at the beginning and the end of the study (1994 and 1999)

<table>
<thead>
<tr>
<th>Year</th>
<th>North-facing slope</th>
<th>South-facing slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ScраЪed-sterilized</td>
<td>ScраЪed-crumbled</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1994</td>
<td>0a</td>
<td>3 ± 0.9b</td>
</tr>
<tr>
<td>1999</td>
<td>36.3 ± 8.0a</td>
<td>87.5 ± 15.7a</td>
</tr>
</tbody>
</table>

Mean±SE values with different letters are significantly different at p<0.05 within a slope type.

Table 3
Chlorophyll content of the three treatments: scraped-sterilized, scraped-crumbled, and control plots in the north-facing slopes in 1995 and 1998

<table>
<thead>
<tr>
<th>Year</th>
<th>North-facing slope</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ScраЪed-sterilized</td>
</tr>
<tr>
<td>1995</td>
<td>0.1 ± 0.1a</td>
</tr>
<tr>
<td>1998</td>
<td>0.9 ± 0.8a</td>
</tr>
</tbody>
</table>

Results expressed in mg l$^{-1}$. Mean±SE values with different letters are significantly different at p<0.05 within a slope type.
et al., 1989; Offer et al., 1998). Nevertheless, the successional rate in the plots with the barriers was, in some of the years, even greater than in the open plots (Figs. 2e and f). One explanation for this phenomenon may be that the low plastic barriers provided protection from the wind, cast a shadow that maintained higher soil moisture longer, served as a surface for accumulation of dew and reduced drying, offering the closed plots an advantage over the open plots (Goossens and Offer, 1994).

Comparisons between the two slopes shows significant differences in the NDVI values ($p<0.001$) for the north-facing slope. These differences were also found after the disturbances (Fig. 2a and b), indicating that the differences are due to the characteristics of the slopes.

This study confirms our hypothesis that it is possible to use spectral reflectance measurements of microphytic communities after disturbances as a monitoring technique for following the successional trends of BSCs. In some studies, different methods are discussed regarding measurements of these BSCs (Belnap, 1993; Johansen, 1993). We propose using this spectroscopic method instead because the classical methods for monitoring crust cover and activity (percentage of crust cover, chlorophyll quantification and phytomass) require a greater expenditure of time and money and because they are highly correlated with the NDVI. Spectroscopy does not interfere with nor cause damage to the crusts; sample removal is unnecessary, as it is with other techniques. Moreover, the spectral reflectance method facilitates scanning of large numbers of samples in the field, enabling undisturbed successional trends to be observed. Therefore, this method is recommended for tracking BSC-rehabilitation processes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jaridenv.2007.01.004.

References


