Spectral Characteristics of Cyanobacteria Soil Crust in Semiarid Environments

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Large areas of sand fields in arid and semiarid regions are covered by cyanobacteria soil crusts. The objective of this article is to analyze (systematically throughout the VIS, NIR, and the SWIR regions of the spectrum) the unique spectral features of cyanobacteria crust relative to bare sands and under different moisture conditions. It was found that: 1) When biogenic soil crusts are wet, their NDVI value can reach 0.30 units due to their photosynthetic activity; 2) the closer the red edge inflection point is to the longer wavelengths, the higher the relative abundance and distribution of the microphytic community; 3) the phycobilin pigments, which are unique to cyanobactria, contribute to higher reflectance in the blue region relative to the sand substrate; 4) a crust index based on this uncommon spectral feature can be useful for detecting and mapping, from remote sensing imagery, different lithologic/morphologic units; 5) although most dune sand areas are generally made of quartz, other notable features appear on their spectra. In the study area, there are absorption features representing minerals (iron oxides at 860 nm and clay minerals at 2200 nm) and biogenic crusts (chlorophyll at 670 nm and organic matter at 1720 nm, 2180 nm, and 2309 nm).

INTRODUCTION

Many arid and semiarid surfaces, whether soils or rocks, are covered by biogenic crusts of different microphytic communities comprising mosses, lichens, liveworts, algae, fungi, cyanobacteria (used to be called blue-green algae), and bacteria (West, 1990). This phenomenon has been reported from the Middle East, the African Sahel and the Sahara, North and South America, Central Asia, Australia, and from other locations.

Over sand dune environments, cyanobacteria are the most common component of the crust but are often accompanied by soil algae, mosses, and lichens. Their structure is similar to that of bacteria, but their photosynthetic mechanism resembles that of the green algae. Cyanobacteria have the common chlorophyll *a* but also phycobilin pigments. Many are able to fix atmospheric nitrogen which is needed for proteins. All these features make it possible for them to occupy an ecological niche in the desert where others cannot live due to extreme high temperatures, high pH, and salinity.

The cyanobacteria crust constitutes a relatively small portion of the soil profile, only one to a few millimeters, but since it occupies the uppermost part of the profile, it plays an important role in the desert ecosystem. The cyanobacteria crust, due to the adhesive properties of its filaments, stabilizes the mobile sand dune and prevents water and wind soil erosion (Danin, 1991). The composition of cyanobacteria together with relative high content in silt and clay particles change the soil water regime by affecting runoff, rain interception, water infiltration and percolation, surface evaporation, water-holding capacity, and soil moisture content (Lange et al., 1986; Yair, 1990; Zombre et al., 1996; Verrecchia et al., 1995; Kidron and Yair, 1997). It also improves soil fertility due to changes in the content of different elements such as amino nitrogen, oxygen, organic carbon, nutrients, and more (Shields et al., 1957). The existence of microphytic communities in the topsoil provides a starting material for the production of other soil components (Shields and Drouet, 1962). From the remote sensing point of view Karnieli et al. (1996) have shown that when the biogenic crust is wet,

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its spectral reflectance values can be similar to those of higher plants and therefore may lead to misinterpretation of the vegetation dynamics and to overestimation of ecosystem productivity when using some remote sensing parameters such as vegetation indices.

Although large areas of sand fields in arid and semiarid regions are covered by the cyanobacteria soil crusts, relatively limited research has been conducted to investigate their spectral characteristics and their dynamic behavior under dry and wet conditions. Only a small number of articles represent spectral curves of cyanobacteria crusts. These are—O'Neill, 1994; Karnieli and Tsoar, 1995; Pinker and Karnieli, 1995; Tromp and Steenis, 1996; Zombré et al., 1996; Tsoar and Karnieli, 1996; Karnieli et al., 1996; Karnieli and Sarafis, 1996; and Karnieli, 1997. None of the above has analyzed systematically the unique spectral features of the cyanobacteria crust throughout the visible (VIS), near-infrared (NIR), and the short-wave infrared (SWIR) regions with respect to bare sands and under different moisture conditions. This article addresses the above issues.

STUDY AREA

The study area, known as the Sede Hallamish dune field along the Israel/Egypt political border, about 50 km south of the Mediterranean coastline (34°23′E/30°57′N) (Karnieli and Tsoar, 1995; Karnieli, 1997), is characterized by sandy linear dunes. Rainfall has a long-term annual average of 100 mm and is restricted only to the winter period (October–March). The average minimum daily temperatures are 5°C in January and 19°C in July. The average maximum daily temperature is 16°C and 33°C in January and July, respectively.

A typical sandy dune ridge can be subdivided into several lithologic/morphologic units (Yair, 1990). The upper parts of the sand ridge (dune crests) cover some 10% of the area. The basal dune and interdune corridors extend over some 85% of the area and are almost totally covered by biogenic crust of (mostly) cyanobacteria which is associated with fine-grained soil particles (silt and clay, 15–20%) (Danin et al., 1989; Lange et al., 1992). Five microphytic communities were defined in the Sede Hallamish dune field (Kidron, 1995). These are denoted in this article as Communities A, B, C, D, and E. Only the first community (A), consisting of *Microcoleus sociatus*, *M. vaginatus*, and *Phormidium* sp., extends over the lower slopes facing the south and over the interdunes. The other four communities (B to E) occupy the north facing hill slopes of the dunes and in addition to the above cyanobacteria species, they consist of *Nostoc microscopicum, Scytonema* sp., *Oscillatoria* sp., *Schizotrix friesii*, and *Chroococcidiopsis* sp., green algae (*Chlorococcum* sp., *Stichococcus* sp.) and two species of mosses, *Bryum dunnense* and *Tortula brevissima.* The species composition is presented in Table 1.

Despite the difference in species composition, the five communities also differ in their physico-chemical properties as well as in their microbiological characteristics, namely, chlorophyll content, organic matter, polysaccharides content, and protein content, as well as crust thickness. All show consistent increase from Community A to E (Table 2). In addition, this table shows, based on the Munsell color system, that the soil become gradually darker from Community A to E, either under dry or wet conditions.

METHODOLOGY

Soil samples (either sand or crust) free of vascular plants were collected by scraping the soil surface to one centimeter depth. The samples were stored in Petri dishes and processed a short time after. Two different sets of sampling were conducted. The first set was sampled in September 1996 when the soil was completely dry. This set includes crust samples of Communities A, B, C, D, and E. The spectral characteristics of the cyanobacteria crusts were studied *in vivo* in the laboratory by using a Li-Cor LI-1800 portable spectrometer. The spectrometer was fixed to a spectral resolution of 2 nm between 400 nm and 1100 nm and 15° field of view (FOV). After spectral measurements under dry conditions (denoted in this article as "dry" samples), the samples were wetted with double distilled water and incubated under a fluorescent illumination of 95 μE m^{-2} s^{-1} at 22°C. Additional spectral measurements were conducted after 1 day (denoted as "wet+1" samples) and after 7 days (denoted as "wet+7" samples). Greening of the crust appeared usually after a few hours, but its chlorophyll content was studied only after a week, when it was fully developed.

The second set was sampled in the winter in March 1997. Until the sampling day the area had received 76.9 mm of rain, most of it in January. Only 0.2 mm of rain fell one day before sampling. The set includes crust samples only from communities A, C, and E as well as pure dune sand. The samples were measured in the laboratory by using the GER IRIS MARC V. This spectrometer has a fixed spectral interval of 2 nm between 350 nm and 1000 nm and 4 nm between 1000 nm and 2500 nm, and 3×7° rectangular FOV. The major advantage of the GER spectrometer is its ability to measure in the SWIR region. Since the samples were measured a short time after collection, they were not completely dry.

Laboratory measurements, with constant light intensity and geometry, eliminate the time and space dependence of the measurements and provide a full control of the sample condition, for example, water content, stage of growth, or microphytes percent cover. The optical heads (for both instruments) were installed about 0.5 m above the sample, at nadir. The illumination source, a 1000 W quartz halogen lamp, were positioned at 45° zenith angle, approximately 0.5 m away from the sample.

Table 1. Microphytic Communities at the Sede Hallamish Site[a]

Species	Community A	B	C	D	E
Microcoleus sp.	*****	*****	****	****	***
Phormidium sp.	***	**	**	*	*
Scytonema sp.	*	**	***	****	***
Nostoc microscopicum	*	*	**	***	***
Oscillatoria sp.	s	*	**	***	***
Schizothrix friesii	s	*	**	***	***
Chroococcidiopsis sp.	s	s	s	*	*
Green algae	s	s	*	**	***
Mosses	5.5×10^2	8.3×10^2	3.3×10^3	4.7×10^4	7.8×10^5

[a] Asterisks represent the relative abundance of the different microphytic communities where one asterisk stands for low, five for high and "s" stands for scarce, except for the moss cover which is given in individual counts per square meter.

The samples were laid on a black coated board to minimize external reflectance or backscatter. For the Li-Cor measurements, the spectral measurements of a halon reflectance panel were obtained at the beginning of each data set, to be used as reference for the reflectance calculations. The GER is a double beam instrument and the barium sulfate ($BaSO_4$) reference panel was read simultaneously with the samples. The reflectance values were determined by dividing each sample spectrum by the panel spectrum. The samples were rotated 90° between scans to prevent micro relief effect on the illumination, and the final result for each sample is the average of the four measured spectra.

In order to examine the contribution of the phycobilin pigments to the blue color, these pigments were removed by using the method described by Siegelman and Kycia (1973). The method involves taking a crust and inundating it in a 0.05 M potassium phosphate buffer at pH 6.8. The sample was then frozen and thawed twice in the buffer. After thawing the sample was washed for 15 min in the buffer and then treated in 2 mg/mL of egg white lysozyme (L6876 Sigma) in the same buffer for 8 h. A phosphate buffer rinse was given for 15 min, and the sample was then placed in the fresh lysozyme solution as above for about 2 h. The sample was then frozen and thawed once more and rinsed in distilled water. Reflectance spectra were obtained, using the Li-Cor spectrometer, from the reference crust prior to wetting, after wetting, after the first two freeze thaw cycles and the last freeze thaw cycle to determine the loss of phycobilins.

ANALYSIS AND RESULTS

Laboratory spectral measurements, using the Li-Cor spectrometer, which demonstrate the microphytes' response to wetting are presented in Figure 1. Figure 1a shows the five communities (Table 1) under dry conditions. Generally, all curves have the same spectral features, but they differ in the overall magnitude of reflectance and the depth of the pigment absorption zone. The spectrum which represents the fewest microphytic species (Community A) is characterized by very slight absorption features in the red and is very much like a typical bare soil spectrum, for example, relatively low in the blue region and increasing gradually towards the near infrared region. The higher the number of species and the related biomass, the deeper the absorption features in the red and the lower the reflectance due to gradual darkening of the crust. In spite of this absorption feature which characterizes green vegetation, the other indicators of higher plants are hardly identifiable: There is no peak at 550 nm, and the slope angle of the increase in spectral reflectance around 700 nm is relatively gentle. Figures 1b and 1c represent the same communities after

Table 2. Physiological and Soil Parameters of Microphytic Communities at the Sede Hallamish Site[a]

Community	Chlorophyll Content (g/m^2)	Organic Matter (%)	Polysacch. Content (g/m^2)	Protein Content (g/m^2)	Crust Thickness (mm)	Soil Color Dry	Soil Color Wet
A	0.017	0.5	4.71	3.72	1.1	10YR6/4	10YR5/4
B	0.021	0.6	7.71	5.29	1.5	10YR6/4	10YR5/3
C	0.029	0.7	8.27	5.51	2.0	10YR6/4	10YR4/4
D	0.041	0.9	14.35	9.31	2.8	10YR6/3	10YR4/3
E	0.053	2.6	30.60	28.37	10.0	10YR6/3	10YR3/3

[a] All values increase from community A to E as a function of the relative abundance and distribution of the microphytes. Community E, which consists mostly on mosses has relatively higher values.

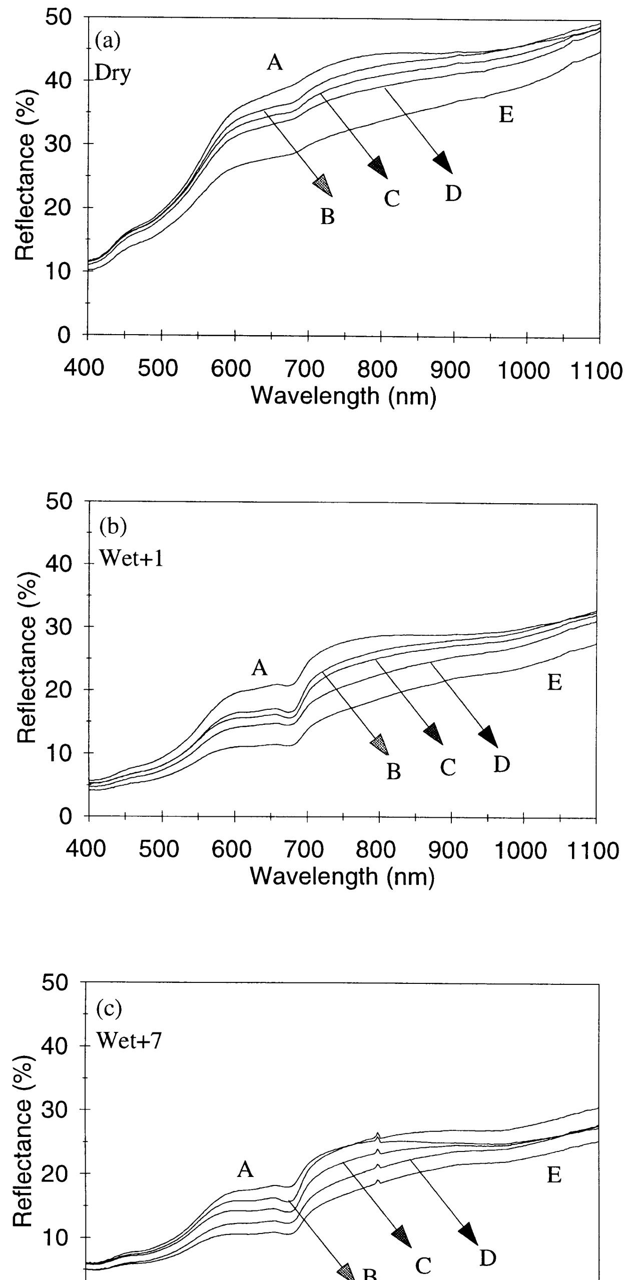


Figure 1. Spectral response of different microphytic communities (A, B, C, D, E) in the Sede Hallamish study site under different moisture conditions: a) dry samples; b) samples after wetting and 1 day of incubation; c) samples after wetting and 7 days of incubation. Note that the spectral signals decrease from community A to E as a function of the relative abundance and distribution of the microphytes, and also due to the wetting schedule.

1 day and 7 days of incubation, respectively. It can be noticed that as the incubation process continues their reflectance level is lower than that of the dry crust and exhibit a significant dip in the red region.

The calculated values of the normalized difference vegetation index, NDVI=(NIR−RED)/(NIR+RED), where NIR and RED are reflectance in the near-infrared and red wavebands, respectively, are presented in Table 3. For each moisture condition, for example, dry, wet+1 day, and wet+7 days, the NDVI values increase with respect to the relative abundance of the different microphytic communities and their biomass. In addition, it can also be seen that in each community the NDVI values increase with respect to moisture condition. When dry, the mean NDVI value is as low as 0.08 units, which is typical for dry soil and rocks (Karnieli et al., 1996). Note that since the pure dune sand is relatively bright and almost does not change its color upon wetting, the outcoming NDVI values remain almost constant. Therefore, it can be concluded that the microphytic NDVI is caused mostly due to the photosynthetic activity rather than the increase in the soil moisture content. The highest observed NDVI value is close to 0.30 units. It is also important to note that the biggest temporal change occurs during the first day of incubation. The NDVI value for each community increases on the average by 2.7 times. Although the level of the reflectance continues to decrease after 7 days of incubation, the rate of change of the NDVI values is much smaller.

Table 3 also presents the chlorophyll content of the microphytic communities under dry and wet+7 conditions. As expected, the chlorophyll content of the dry samples are relatively low (about 0.032 g/m^2 on the average). Much higher values were measured under the wet+7 conditions. Here, a high direct correlation between the wet+7 NDVI and chlorophyll content at the same stage was found (r=0.89). Although the number of samples is fairly low for such statistics, about the same correlation coefficient was found for a much higher number of measurements from other regions (Karnieli, unpublished data). Direct relationship also was found between the NDVI values and the organic matter, polysaccharides content, protein content, and crust thickness as well as with the number of species identified in each community.

In higher vegetation, the sharp increase in spectral reflectance around 700 nm, denoted as the *red edge*, marks the transition from the maximum absorption region of the chlorophyll pigment to the maximum reflectance region. Every factor that produces a relative variation of the reflectance in the visible or NIR spectral bands can also change the location of the red edge and the inflection point by about 10 nm along the wavelength axis. This phenomenon is known as the *blue shift* (or sometimes *red shift*, depending on the direction of the movement). When reflectance increases in the NIR, due to water stress for example, the inflection point shifts towards the shorter wavelengths and vice versa. Consequently, the shift is a function of the plant status and is usually used as an important indicator for detecting phenological changes and plant stresses (Collins, 1978; Horler

Table 3. NDVI and Chlorophyll (g/m[2]) Values for the Sand Dune and Microphytic Communities at the Sede Hallamish Site in Different Moisture Conditions[a]

	Dry		*Wet+1*		*Wet+7*	
Community	*NDVI*	*Chl.*	*NDVI*	*Chl.*	*NDVI*	*Chl.*
Sand	0.07	N/A	0.08	N/A	0.08	N/A
A	0.06	0.017	0.14	N/A	0.15	0.076
B	0.08	0.021	0.22	N/A	0.23	0.100
C	0.08	0.029	0.23	N/A	0.24	0.193
D	0.08	0.041	0.23	N/A	0.27	0.249
E	0.10	0.051	0.27	N/A	0.29	0.318

[a] N/A means data not available. Note that both NDVI and chlorophyll values increase from community A to E with respect to the relative abundance and distribution of the microphytes, and also due to the wetting schedule.

et al., 1980; 1983; Ferns et al., 1984; Guyot et al., 1992). The red edge location in terms of wavelengths is usually calculated by the second derivative of the reflectance. Figure 2 presents the second derivative of reflectance for the different communities and shows a progressive red shift from Community A to E. The inflection point of the poorest community is located at the shorter wavelength (about 692 nm) while that of the richest community is at the longer wavelength (about 695 nm).

The other set of measurements, using the GER spectrometer, is presented in Figure 3. This figure shows the spectra of active sand dune and three microphytic communities in the visible, NIR, and the SWIR regions (400–2500 nm). The active sand was sampled on the dune crest. The sand spectrum demonstrates that in addition to quartz (the major mineral of dune sand), iron oxide and clay minerals features are also evident at 860 nm and 2200 nm, respectively, and there is a clue for carbonates at 2330 nm. These findings were verified against X-ray analysis that shows that about 95% of the sample consist of quartz and the remaining 5% of impurities such as calcite, feldspar, and clay minerals. The two other distinctive absorption features at about 1400 nm and 1900 nm are related to structural water.

In this set of measurements, the microphytes were sampled in the interdune (Community A) and in the north-facing slope (Communities C and E), as described in Table 1. The microphytic spectra have somehow a similar shape to that of the sand but lower level of reflectance. An interesting feature in Figure 3 is that the cyanobacteria crust (Communities A and C) spectra have higher reflectance than the pure sand spectrum only in the blue region. These three curves cross each other in the green region (550 nm). Also, the mosses-based spectrum of Community E, although much lower than the sand spectrum and not crossing it, shows a gentler slope in the blue region. In the SWIR, several broad and shallow absorption features that are related to organic matter are observed, especially in Community E. These are at

Figure 2. The red edge of the different communities (A, B, C, D, E) in the Hallamish study site. By calculating the second derivative of the specta, zero values represent the inflection point of the red edge. It is shown that the closer the red edge inflection point is to the longer wavelengths, the higher the relative abundance and distribution of the microphytic community.

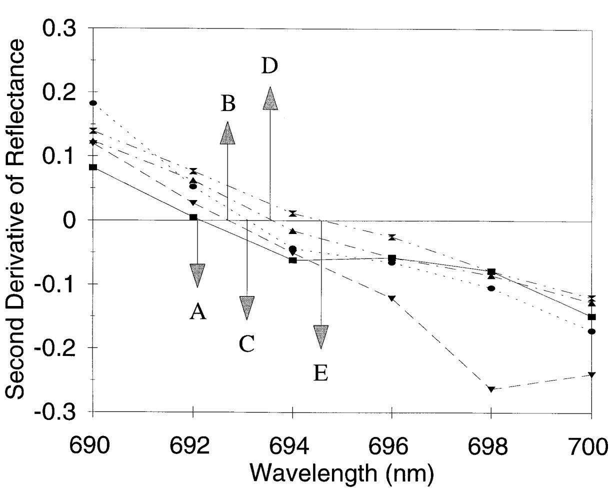
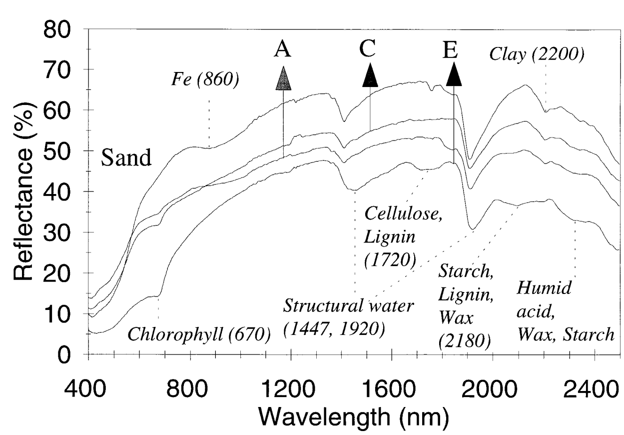


Figure 3. Spectra of active sand dune and microphytic communities A, C, and E. Main absorption features are pointed in nanometers.



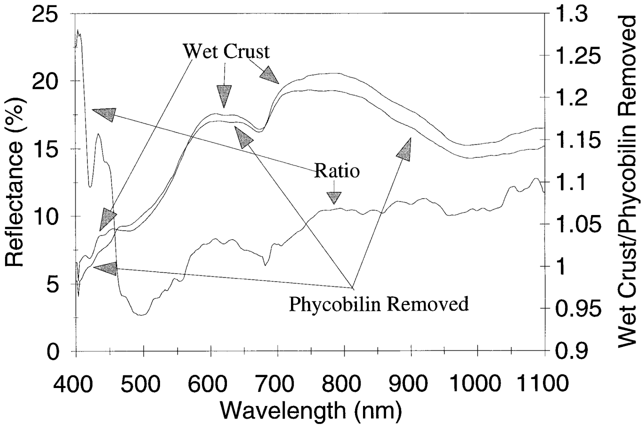


Figure 4. Spectra of wetted cyanobacteria crust, phycobilin extracted crust, and the ratio between them. It is shown that relative high reflectivity of the crust in the blue region is due to the spectral characteristics of the phycobilin pigments.

1720 nm (assigned for fresh organic matter to: cellulose/lignin/starch/pectin), 2180 (assigned for fresh organic matter to: starch/lignin/wax/tannis), and 2309 (assigned for fresh organic matter to: humic acid/wax/starch) (Ben-Dor et al., 1997). Note that organic matter elements are also located at 1447 nm and 1920 nm, but they are masked by the water absorption bands (Elvidge, 1990; Ben-Dor et al., 1997). Here these bands are weaker than in the sand spectrum and shift towards the longer wavelengths.

Figure 4 presents the reflectance spectra of the wetted crust and the phycobilin extracted crust, as well as the ratio between them. After removing the pigments, decrease in the reflectance is noted in the blue region while virtually no change is observed in the red region. This indicates successful leaching of phycobilin pigments (and not of the chlorophyll pigments) and confirms the contribution of the phycobilins to the (blue) color of the crust.

DISCUSSION

Microphytes play a significant role in arid land biological processes. There are evidences (Antonova et al., 1986) that the microphytes' biomass is greater than that of the foliage part of higher plants. However, from the remote sensing point of view, biogenic crusts are usually considered as soil rather than vegetation. Since the microphytes are poikilohydrous plants, they respond quickly to the wetness of their sandy substrate and change from dormant mode to an active mode. A few minutes after wetting, they start respiring, change their color to green, and revert to full photosynthetic activity. In that case their spectral response is similar to that of higher plants. When the crusts become dry again, they return into the previous dormant mode even for a long period of time. Changing their active/dormant modes can be repeated innumerable times. Considerably high NDVI values of 0.30 units over large areas may lead to misinterpretation of the spectral signal, such as overestimation of vegetation biomass or productivity. In this case it is important to separate the spectral signal of higher plants from that of the microphytes and to estimate the contribution of the latter to the overall desert biomass, productivity, carbon cycle, etc. As a first step, the current research shows high correlation between the chlorophyll concentration and the NDVI values.

The shift of the red edge along the wavelength axis towards the blue is usually interpreted as an indicator of vegetation stress since both the position and the slope of the rise near 700 nm change as the leaf goes from active photosynthesis to total senescence. In the current examples it has been shown that the blue (or red) shift is also an indicator for the relative abundance and distribution of the microphytic community.

The unique spectral feature described in the section above (i.e., higher reflectance level of crusted surfaces with cyanobacteria relative to bare dune sands) has been observed in several other dune fields, such as in Egypt (Jacobberger, 1989), in Burkina Faso (Tromp and Steenis, 1996; Zombré et al., 1996), in Niger (Houssa et al., 1996); and in Senegal (Karnieli and Glaesser, unpublished). It seems that this phenomenon is worldwide. From the phycobilin extraction experiment (Fig. 4) it can be concluded that the relative higher reflectivity of the crust in the blue region is due to the spectral characteristics of the phycobilins. These pigments are unique for cyanobacteria and generally not detectable in higher plants. They are protein pigments containing a linear tetrapyrrol as the chromophore. Rippka (1988) mentioned that the phycobilins are the major contributors of the cyanobacterial color. Karnieli (1997) took advantage of this unique spectral phenomenon of soil biogenic crust for developing a spectral crust index (CI) based on the normalized difference between the RED and the BLUE spectral values: $CI=1-(RED-BLUE)/(RED+BLUE)$. By applying the index to the sand dune environment, it was shown that the CI can be used to detect and to map, from remote sensing imagery, different lithologic/morphologic units such as active sands, crusted interdune areas and playas, which are expressed in the topography. As a mapping tool, the CI image was found to be much more sensitive to the ground features than the original image. The application of the CI can be performed with imagery acquired by any sensor that contains the blue band. Currently, the most common data sources are color aerial photographs and Landsat-TM images as demonstrated in Karnieli (1997). However, CI should be applicable to other sensors such as the SPOT-VEGETATION, MOMS-2P, SeaWiFS, JERS-OPS, and MODIS which will be available in the coming years. Since the proposed algorithm is based on the blue band, the CI is susceptible to atmospheric effects that may impair the index's value when applied to

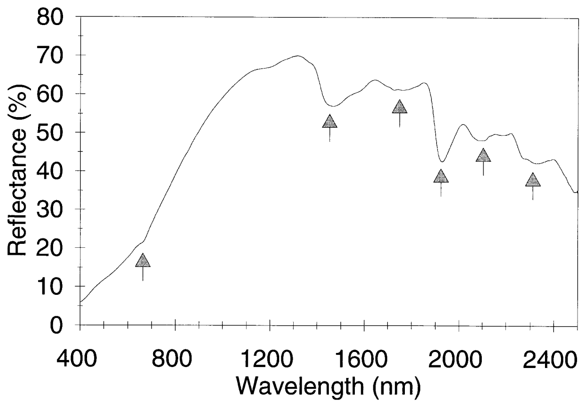


Figure 5. Spectrum of a fresh organic matter (after Ben-Dor et al., 1997). Arrows indicate the main absorption features that were also found in the spectrum of the biogenic crust (Fig. 3).

remote sensing data. Consequently, any image should be atmospheric corrected before using the CI.

From the spectra presented in Figure 3 it is evident that significant changes occur from the sand spectrum to Community E. The iron oxide and the clay minerals absorption features at 860 nm and 2200 nm, respectively, diminish gradually from the sand's spectrum to that of Community E. On the other hand, the chlorophyll dip at 670 nm becomes deeper along the same gradient. Since both the biological materials and minerals form the thick crust layer over the quartz particles, together they affect the spectral response of the ground surface. As more intense biogenic crust forms, the iron oxide and the clay minerals absorption features are masked and the organic matter features become dominant. In this respect, water absorption features at 1447 nm and 1920 nm do not hold similar sequence. This is because, in the case of the minerals, water molecules are located at the particles' surface as hygroscopic water while in the case of the biogenic material, water molecules are an integral part of the microphytes structure. These features are very sensitive to external conditions (e.g., relative humidity, temperature, etc.) which probably were not constant at measurement time.

A careful inspection of the spectrum of Community E in Figure 3 reveals that the biogenic crust spectrum shows a remarkable similarity to a fresh organic matter spectrum as presented in Figure 5. The latter spectrum was generated from a dry solid fibrous fraction of a cattle manner that was put into composting process for more than a year and detailed spectrally investigated (Ben-Dor et al., 1997). The similarity of the two spectra suggests that in both materials the same functional groups are active. The wavelengths of 1720, 2180, and 2309 nm were associated with different elements of fresh organic matter by Ben-Dor et al., 1997. Chemical analysis of the biogenic crust (Table 2) verifies that the protein and the polysaccharides contents are relatively high in Community E. These elements are 2 and 3 times higher (respectively) than in Community D. Therefore, it is strongly believed that other related features of the biogenic crust in sample E are also part of the organic matter component. It also should be noted that the chlorophyll content increased by about 25 per cent from community D to E whereas the organic matter content increased by about 300 per cent. This might explain why the organic matter features are dominant.

Since the spectra of Community E and the fresh organic matter have a significant similarity, precautions must be taken in any spectral analysis. For that reason, the 670 nm chlorophyll trough must be temporally examined. Ben-Dor et al. (1997) reported that fresh organic matter tends to lose the chlorophyll peak after about 60 days if ideal decomposition conditions are present. Because the biogenic crusts are live tissues and organic matter is dead, the 670 nm trough that vanished with time suggests that the sensed matter is organic matter and the dip that fluctuated with time is biogenic crust-related. If biogenic crust is present, precautions must be taken not to misclassify biogenic crust as organic matter and vise versa. A temporal spectral inspection, using the chlorophyll peak as an internal indicator may provide a significant answer to the sand/crust question.

The three organic matter absorption bands and especially the bands around 1720 nm and 2180 nm can be used for identifying biogenic crust cover with airborne or spaceborne imagery since only a few minerals have both spectral features. Ager and Milton (1987) and Rollin et al. (1994) came to the same conclusion with respect to lichens.

CONCLUSIONS

- When biogenic soil crusts are wet, their NDVI value can reach up to 0.30 due to their photosynthetic activity. This may lead to misinterpretation of the spectral signal, such as overestimation of vegetation biomass or productivity.
- The shift of the red edge inflection point towards the longer wavelengths is an indicator for the relative abundance and distribution of the microphytic community.
- The phycobilin pigments, which are unique to cyanobactria, contribute to higher reflectance in the blue region relative to the sand substrate. Based on this uncommon spectral feature, a crust index can be useful for detecting and mapping, from remote sensing imagery, different lithologic/morphologic units.
- Although most of the studied dune sand areas (as well as most other similar sand fields around the world) are generally made of quartz, other

notable features are present in their spectra. The absorption features representing the minerals are iron oxides (at 860 nm wavelength) and clay minerals (at 2200 nm) and those representing the biogenic crusts are chlorophyll (at 670 nm) and organic matter (at 1720 nm, 2180 nm, and 2309 nm). The above spectral features change progressively from the sand spectrum to the highest biomass biogenic crust spectrum. Also, the water absorption features (at 1400 nm and 1900 nm) become weaker and shift towards the longer wavelengths.

REFERENCES

Antonova, C. G., Nechaeva, N. T., and Dourikov, M. (1986), Dynamics of mosses' cover distribution in the ridge-takyr complex of Central Karakum Desert. *Problems Desert Dev.* 2:35–45 (in Russian).

Ager, C. M., and Milton, N. M. (1987), Spectral reflectance of lichens and their effects on the reflectance of rock substrates. *Geophys.* 52:898–906.

Ben-Dor, E., Inbar, Y., and Chen, Y. (1997), The reflectance spectra of organic matter in the visible near infrared and short wave infrared region (400–2,500 nm) during a controlled decomposition process. *Remote Sens. Environ.* 61:1–15.

Collins, W. E. (1978), Remote sensing of crop type and maturity. *Photogramm. Eng. Remote Sens.* 44:43–55.

Danin, A. (1991), Plant adaptation in desert dunes. *J. Arid Environ.* 21:193–212.

Danin, A., Bar-Or, Y., Dor, I., and Yisraeli, T. (1989), The role of cyanobacteria in stabilization of sand dunes in southern Israel. *Ecol. Mediterranea* 15:55–64.

Elvidge, C. D. (1990), Visible and near infrared reflectance characteristics of dry plant material. *Int. J. Remote Sens.* 11:1775–1795.

Ferns, D. C., Zara, S. J., and Barber, J. (1984), Application of high spectral resolution spectroradiometry to vegetation. *Photogramm. Eng. Remote Sens.* 50:1725–1735.

Guyot, G., Baret, F., and Jacquemoud, S. (1992), Image spectroscopy for vegetation studies. In *Imaging Spectroscopy: Fundamentals and Prospective Applications* (F. Toselli and J. Bodechtel, Eds.), Kluwer Academic, Dordrecht, pp. 145–165.

Horler, D. N. H., Barber, J., and Barringer, A. R. (1980), Effect of heavy metals on the absorbence and reflectance spectra of vegetation. *Int. J. Remote Sens.* 1:121–136.

Horler, D. N. H., Dockray, M., and Barber, J. (1983), The red edge of plant leaf reflectance. *Int. J. Remote Sens.* 4:273–288.

Houssa, R., Pion, J.-C., and Yesou, H. (1996), Effects of granulometric and mineralogical composition on spectral reflectance of soils in sahelian area. *Photogramm. Remote Sens.* 51:284–298.

Jacobberger, P. A. (1989), Reflectance characteristics and surface processes in stabilized dune environments. *Remote Sens. Environ.* 28:287–295.

Karnieli, A. (1997), Development and implementation of spectral crust index over dune sands. *Int. J. Remote Sens.* 18:1207–1220.

Karnieli, A., and Tsoar, H. (1995), Spectral reflectance of biogenic crust developed on desert dune sand along the Israel-Egypt border. *Int. J. Remote Sens.* 16:369–374.

Karnieli, K., and Sarafis, V. (1996), Reflectance spectrometry of cyanobacteria within soil crusts—a diagnostic tool. *Int. J. Remote Sens.* 17:1609–1615.

Karnieli, A., Shachak, M., Tsoar, H., et al. (1996), The effect of microphytes on the spectral reflectance of vegetation in semiarid regions. *Remote Sens. Environ.* 57:88–96.

Kidron, G. J. (1995), The impact of microbial crust upon rainfall-runoff-sediment yield relationships on longitudinal dune slopes. Nizzana, western Negev Desert, Israel, Ph.D. thesis, The Hebrew University of Jerusalem (Hebrew with English summary), 113 pp. (unpublished).

Kidron, G. J., and Yair, A. (1997), Rainfall–runoff relationship over encrusted dune surfaces, Nizzana, western Negev, Israel. *Earth Surface Process. Landforms* 22:1169–1184.

Lange, O. L., Kilian, E., and Ziegler, H. (1986), Water vapor uptake and photosynthesis of lichens: performance differences in species with green and blue-green algae as phycobionts. *Oecologia* 71:104–110.

Lange, O. L., Kidron, G. J., Budel, B., Meyer, A., Kilian, E., and Abeliovich, A. (1992), Taxonomic composition and photosynthetic characteristics of the biological soil crusts covering sand dunes in the western Negev Desert. *Functional Ecol.* 6:519–527.

O'Neill, A. L. (1994), Reflectance spectra of microphytic soil crust in semi-arid Australia. *Int. J. Remote Sens.* 15:675–681.

Pinker, R. T., and Karnieli, A. (1995), Characteristic spectral reflectance of semi-arid environment. *Int. J. Remote Sens.* 16:1341–1363.

Rippka, R. (1988), Recognition and identification of cyanobacteria. In *Methods of Enzymology*, Cyanobacteria, Vol. 167 (L. Packer and A. N. Glazer, Eds.), Academic, San Diego, pp. 28–93.

Rollin, E. M., Milton, E. J., and Roche, P. (1994), The influence of weathering and lichen cover on reflectance spectra of granitic rocks. *Remote Sens. Environ.* 50:194–199.

Shields, L. M., and Drouet, F. (1962), Distribution of terrestrial algae within the Nevada test site. *Am. J. Bot.* 49:547–554.

Shields, L. M., Mitchell, C., and Drouet, F. (1957), Alga- and lichen-stabilized surface crusts as soil nitrogen sources. *Am. J. Bot.* 44:489–498.

Siegelman, H. W., and Kycia, J. H. (1973), Algal biliproteins. In *Handbook of Phycological Methods. Physiological Methods and Biochemical Methods* (J. A. Hellebust and J. S. Craigie, Eds.), Cambridge University Press, Cambridge, pp. 71–79.

Tromp, M., and Steenis, Z. (1996), Deriving sub-pixel soil characteristics in northern Burkina Faso with spectral unmixing. In *Proceedings of the ISSS International Symposium (Working Groups RS and DM) on Monitoring Soils in the Environment with Remote Sensing and GIS*, 1995, Ouagadougou, Burkina Faso, pp. 269–284.

Tsoar, H., and Karnieli, A. (1996), What determines the spectral reflectance of the Negev-Sinai sand dunes? *Int. J. Remote Sens.* 17:513–525.

Verrecchia, E., Yair, A., Kidron, G. J., and Verrecchia, K. (1995), Physical properties of the psammophile cryptogamic crust and their consequences to water regime of sandy soils, north-western Negev Desert, Israel. *J. Arid Environm.* 29:427–437.

West, N. E. (1990), Structure and function of microphytic soil crust in wildland ecosystems of arid to semi-arid regions. *Adv. Ecol. Res.* 20:179–223.

Yair, A. (1990), Runoff generation in a sandy area—the Nizzana sands, eastern Negev, Israel. *Earth Surface Process. Landforms* 15:597–609.

Zombré, P. N., Pallo, F., Mulders, M. A., et al. (1996), Excursion to the Kaya region, Burkina Faso. In *Proceedings of the ISSS International Symposium (Working Groups RS and DM) on Monitoring Soils in the Environment with Remote Sensing and GIS*, 1995, Ouagadougou, Burkina Faso, pp. 569–592.