Development and implementation of spectral crust index over dune sands

A. KARNIELI
The Remote Sensing Laboratory, J. Blaustein Institute for Desert Research, Ben Gurion University, Sede-Boker Campus 84990, Israel

(Received 26 January 1996; in final form 19 July 1996)

Abstract. Advantage is taken of a unique spectral feature of soil biogenic crust containing cyanobacteria. It has been shown that the special phycobilin pigment in cyanobacteria contributes in producing a relatively higher reflectance in the blue spectral region than the same type of substrate without the biogenic crust. A spectral crust index (CI) has been developed, based on the normalized difference between the RED and the BLUE spectral values: \[ CI = 1 - \frac{(\text{RED} - \text{BLUE})}{(\text{RED} + \text{BLUE})} \]. Applying the index to a sand dune environment, it has been shown that the CI can be used to detect and to map, from remote sensing imagery, different lithological morphological units, such as, active sands, crusted interdune areas and playas, which are expressed in the topography. As a mapping tool the CI image is much more sensitive to the ground features than the original images. The absence, existence, and distribution of soil crust are an important information for desertification and climate change studies. They are also highly valuable information for developing agricultural regions and/or infrastructures in arid environments since soil crusts contribute to soil stability, soil build-up, soil fertility, and to the soil water regime. The application of the proposed CI can be performed with imagery acquired by any sensor which contains the blue band. Currently, the most common data sources are colour aerial photographs and Landsat TM images as demonstrated in this paper. However, CI should be applicable to other sensors such as the SPOT-VEGETATION, MOMS-2P, SeaWiFS and MODIS which will be available in the coming years.

1. Introduction

Soil crust formation is a common and widespread phenomenon in arid and semi-arid soils. Distinction should be made between physical and biogenous crust formations. 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).

The biogenous soil (also known as organic or microphytic crust) can be formed by different combinations of microphytic communities including mosses, lichens, liverworts, algae, fungi, cyanobacteria (= blue-green algae or Cyanophyta), as well as bacteria (West 1990). The microphytes can grow on different rocky materials such as limestone, chalk, dolomite, flint, sandstones, granite, as well as on different soil types such as loess and dune sand (Evenari et al. 1982, Friedmann and Galun 1974, West 1990). They are well adapted for primary colonization of arid environments due to their extraordinary ability to survive desiccation and extreme temperatures (up to 70°C), high pH and salinity. Consequently, well developed soil crust
Microphytic communities are found on soils in arid and semi-arid areas throughout the world.

Cyanobacteria are usually the primary components of soil crust (Booth 1941), but are often accompanied by soil algae, mosses and lichens. Since cyanobacteria colonize the soil faster than the other microphytes and stabilize the surface, they usually represent an early stage in the soil crust succession.

Although the crust formation, either physical or biogenical, is an almost negligible portion of the soil profile (only one to a few millimetres in thickness) it plays a significant role in desert ecosystems. From the hydrology point of view, it influences runoff, rain interception, water infiltration and percolation, surface evaporation, water holding capacity and soil moisture content (Hillel 1980, Lange et al. 1986, Morin et al. 1989, Yair 1990, Stroosnijer and Hoogmoed 1995, Verrecchia et al. 1995). Geomorphologically speaking, since the crusted soil layer has more silt and clay material due to the adhesive properties of filamentous cyanobacteria and other microphytes than the sandy profile beneath, it prevents soil erosion by water or wind, and is responsible for the stabilization of sand dunes (Danin 1991). Addition of fine particles and organic material to the upper soil layer 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). It happens that the existence of microphytic communities in the topsoil provides a starting material for the production of other soil components (Shields and Drouet 1962). Recently, Karnieli et al. (1996) have shown that when the biogenic crust is wet, 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 methods such as vegetation indices.

However, despite the importance of the soil crust and its vast distribution over arid and semi-arid soils, little is known about the ability to detect and map desert crusts by remote sensing methods. Spectral reflectance curves of different desert microphytic communities are presented by Ager and Milton (1987), O'Neil (1994), Tromp and Steenis (1995), Karnieli and Tsaro (1995), Karnieli et al. (1996) and Karnieli and Sarafis (1996). Some efforts to map biogenic crusts based on Landsat MSS images have been made by Wessels and van Vuuren (1986) and Tsaro and Karnieli (1996). The latter works show the capacity to visually differentiate and classify several types of crusts. The aim of the present work is to map various types of crusts by relating new knowledge about their spectral features to aerial photographs and satellite images.

2. Study area

The study area is located in the northwestern Negev desert (Israel) and northeastern Sinai (Egypt) along the desert transition zone ranging between about 100 mm mean annual rainfall in the south to about 200 mm in the north (Tsaro and Möller 1986; Yair 1990). Although the sand field of the Negev represents the eastern extension of the Sinai fields from the geomorphological and lithological points of view, the area is artificially divided by the political border line. The border line is characterized by a sharp contrast, higher reflectance values (brighter) on the Egyptian side and lower reflectance (darker) on the Israeli side. This contrast has long drawn the attention of many scientists. The traditional and popular explanation asserts that the contrast is mainly due to severe anthropogenic impact of the Sinai Bedouin—especially overgrazing by their black goat and sheep herds, as well as gathering of
Development and implementation of spectral crust index over dune sands

plants for firewood. This interpretation has been pioneered by Ottermann since 1974 and summarized in Ottermann (1996). On the other hand a new theory which was recently proposed by Karniel and Tsoar (1995) and Tsoar and Karniel (1996) suggests that the contrast is not a direct result of severe overgrazing of higher vegetation but is caused by an almost complete cover of biogenic crust in the Israeli side while human and animal activities prevent accumulation of crust, or trample any existing crust, in the Egyptian side.

The sandy area, from the Mediterranean Sea along the Israeli-Egyptian border is not entirely homogeneous but can be subdivided into five geomorphological regions (Tsoar and Karniel 1996). These regions are (from north to south): (A) Coastal dunes generated by young sand encroachment; (B) Sandy soil that underlies the coastal dunes and spreads southwards as a stabilised sandy plain; (C) Low linear dunes with wide interdune areas; (D) High linear dunes with some vegetated crescent-shaped dunes connecting them in the interdune areas; and (E) high linear dunes composed of sand that is redder than the sand in the former region and without any crescent-shaped dune in the interdune area.

Most of the entire area is characterized by sparse higher vegetation cover on the Israeli side of the border which due to the rainfall gradient gradually increases towards the north. On the average it was found that 26 per cent of the area is covered by higher vegetation comprising 11 per cent of annuals and 15 per cent of perennials as sampled in Spring 1993 along with climatic gradient (D. Lavee, unpublished data). On the other hand, it is observed that most of the area (up to 90 per cent) is covered by biogenic crust consisting mostly of cyanobacteria where Microcoleus vaginatus is the dominant species accompanied by Scytonema, Schizothrix, Calothrix, Chroococcidiopsis, Nostoc, and Phormidium. Mosses are relatively rare in the southern part of the study area but are more common in the northern part. Their dominant species are Pterygoneurum, Aloina, Bryum bicolor, Brachymenium exile and Tortula muralis (Danin et al. 1989, Danin 1991, Lange et al. 1992).

Intensive field work has been conducted in the Sede Hallamish site which belongs to the geomorphological region (E) (figure 1). (Several previous papers call the same area ‘Nizzana Site’ (Yair 1990, Lange et al. 1992, Verrecchia et al. 1995)). The typical sandy dune ridge can be subdivided into several lithologic/morphologic units (Yair 1990):

1. Dune crests: the upper part of the sand ridge which covers some 10 per cent of the area in the Israeli side of the border but expands drastically in the Egyptian side, is composed of about 98 per cent unconsolidated active sand. The organic matter content is very low (0·1 per cent). This unit also covers most of the interdune corridors on the Egyptian side.

2. The basal dune and interdune corridors extend over some 85 per cent of the area in the Israeli side and are almost negligible on the other side of the border. The surface is covered by a rather contiguous biogenic crust (as mentioned above) which consists of fines (silt and clay, up to about 40 per cent) and has a relatively high organic matter content (1–2 per cent).

3. Playa surfaces: flat whitish isolated patches of up to a few hundreds of square metres in area. These units which exist on both sides of the border are relics of an old flood plain consisting of up to 70 per cent fines and almost does not contain any microphytic communities. Therefore, the playa crust is considered as a physical crust.
The biogenic crust of cyanobacteria is mainly associated with the fine-grained soil particles. Both the fines and the cyanobacteria have been brought from adjacent deserts by winds. As a result of limited human and animal activity in the Negev region, they have been deposited and trapped by vegetation and accumulated primarily in the interdune areas. Due to the gluey nature of the cyanobacteria, the biogenic crust spreads with time, causing aggregation of more fines. Danin (1991) shows that there is a high correlation ($r^2 = 0.879$) between silt content and percentage of organic material in cyanobacterial crusts. These are results of analyses of 18 crust samples in sites with stable and active dunes in northwestern Negev.

3. Data analyses and results

3.1. Early observations and hypothesis

Field measurements were carried out in situ by using the Li-Cor Li-1800 portable spectrometer. The instrument was fixed to 2 nm wavelength spectral resolution increments between 400 and 1100 nm and $15^\circ$ field-of-view (FOV). The spectrometer was hand held at heights of about 1 m, at nadir. The spectral reflectance was calculated by relating the target radiances to the downwelling irradiation as measured by a cosine-corrected receptor. All measurements were obtained almost simultaneously in the Sede Hallamish site.

Five spectra are presented in figure 2: interdune playa crust, bare active dune sand, and three cyanobacteria crusts sampled at the north and south facing slopes of the basal dune as well as from the interdune crusty surface. These spectra differ from each other by their fines content as presented in table 1. These spectra have a typical soil shape, namely, relatively low in the blue region and increases gradually towards the near infrared region. However, one can notice the slight dip of the crust.
Development and implementation of spectral crust index over dune sands

Figure 2. Spectral reflectance field measurements of different lithologic/morphologic units in the study area with the respective values of the calculated crust index (CI).

Table 1. Soil texture analysis of different lithological/morphological units in Hallamish site.

<table>
<thead>
<tr>
<th></th>
<th>Sand 0.063–2 mm (%)</th>
<th>Silt 0.002–0.063 mm (%)</th>
<th>Clay &lt;0.002 mm (%)</th>
<th>Total fines &lt;0.063 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active dune sand</td>
<td>100.0</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Interdune playa</td>
<td>32.4</td>
<td>44.4</td>
<td>23.0</td>
<td>67.6</td>
</tr>
<tr>
<td>Interdune crust</td>
<td>78.0–84.6</td>
<td>13.1–16.1</td>
<td>2.4–5.9</td>
<td>16.0–22.0</td>
</tr>
<tr>
<td>South facing slope</td>
<td>86.1–86.6</td>
<td>10.3–10.7</td>
<td>2.7–3.6</td>
<td>13.4–13.9</td>
</tr>
<tr>
<td>North facing slope</td>
<td>82.1–84.8</td>
<td>11.2–14.0</td>
<td>3.9</td>
<td>15.2–17.9</td>
</tr>
</tbody>
</table>

spectra from 600 to 700 nm on account of the organic material of the cyanobacteria. The playa spectrum has the highest reflectance values in all bands. The next lower is the active dune sand spectrum which is relatively high in the red and NIR spectral bands while all the other biogenic crust spectra, which are even lower in the red and NIR bands, cross it at different points along the green band, which means that they reflect more in the blue.

The spectral feature described above, i.e. higher reflectance values of crusted samples with cyanobacteria relative to bare dune sand has been observed in several other examples, recently published by Jacobberger (1989), Tromp and Steenis (1995) and Karnieli et al. (1996) (figure 3). Note that in all the spectra where cyanobacteria is involved, either as free algae or in conjunction with lichens, the reference spectrum (bare substrate which consists of either soil or rock without crust or a cut surface) and the crust spectrum cross each other at about 550 nm. The reference curves have higher reflectance in the red and NIR regions and the crust curves have a higher reflectance in the blue region.

The next section is dedicated to testing the hypothesis that the relative higher
reflectivity of the biogenic crust in the blue region is probably caused by the cyanobacteria (which is essentially a blue-green algae).

3.2. Spectral features of cyanobacteria

The identification of cyanophyte containing microphyte crusts by indirect methods poses a problem. Brock (1973) describes the difficulty an ecologist would have in identifying a cyanophyte. According to him, the blue-green colour is hardly diagnostic. Although Rippka (1988) mentions the phycobilins as major determinants of cyanobacterial colour she also drew attention to some of the difficulties in identifying cyanophytes in nature by their colour alone. In this study the potential of in vivo reflectance spectrophotometry as a diagnostic tool has been investigated. The purpose of the experiment was to demonstrate the uniqueness of cyanobacterial crusts. Besides chlorophyll a and assorted carotenoids and xanthophylls, these crusts also contain phycobilins. Phycobilins are generally not detectable in higher plants. They are protein pigments containing a linear tetrapyrrol as the chromophore.
Removal of the phycobilins (Siegelman and Kycia 1973) was carried out in order to assess their contribution to the total reflectance spectra. Note that this method leaves other pigments intact.

Microphytic crusts from the Sede Hallamish site were removed by a spatulate trowel in order to maintain the undisturbed state of the crust. Measurement by reflectance spectrophotometry was carried out using a Li-Cor spectrometer as mentioned above but with an indoor configuration, namely, by using a Tungsten Iodide (Osram) 1000 W lamp as a laboratory light source. Reference calibration was done using a cosine receptor under the same conditions. Spectra were observed at 1 nm intervals from 400 and 1100 nm and were averaged over four readings with 90° rotation between readings.

A reference crust lacking phycobilins was obtained using a variant of the methods 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$^{-1}$ of egg white lysozyme (L6876 Sigma) in the same buffer for eight hours. 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 hours. The sample was then frozen and thawed once more and rinsed in distilled water. Reflectance spectra were obtained 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. The presence of random noise in the spectra was minimized using two average filters sequentially, consisting of moving windows of five and three points successively.

Inspection of the surface of the crust by a binocular dissecting microscope showed the presence of cyanobacteria on the surface of the crust. Microscopic examination of the crusts by means of a compound microscope confirmed the presence of cyanophytes mainly *Microcoleus vaginatus* with some *Nostoc punctiforme* being present as well. 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) colour of the crust.

3.3. *Development and implementation of the crust index*

A colour aerial photograph of Sede Hallamish site is presented in figure 5. The brightest tones (almost white) in this photograph represent the playa areas, less bright tones come from the dune sand areas while the darker tones represent the crusted areas. Brightness profiles of the BLUE and RED bands along A–A transect are drawn perpendicular to the linear dune direction (figure 6). Although high correlation ($r = 0·85$) was found between these two bands, the BLUE/RED ratio emphasizes the relative contribution of the BLUE band. Assuming a spectrum which increases gradually from the blue region towards the NIR, the BLUE/RED value is high (approaching 1) when the BLUE value is as high as the RED values. Figure 6 shows that the ratio is low for the dune sands (<0·625), higher for the interdune crusts (0·625–0·675), and highest for the interdune playas (>0·675). Therefore it can be concluded that the crusts contribute relatively more blue reflectance than the sands.

The unique spectral feature of the biogenic crust discussed in the previous sections...
Figure 4. Spectra of wetted cyanobacteria crust, phycobilin extracted crust, and the ratio between them.

was used for deriving a crust index (CI). This index is aimed at differentiating between crusted and uncrusted areas as well as areas with different fines and organic matter contents. The proposed crust index has the form:

$$CI = 1 - \frac{RED - BLUE}{RED + BLUE} \approx 1 - \frac{NIR - BLUE}{NIR + BLUE}$$

(1)

where BLUE, RED and NIR are the 400–500, 600–700, and 700–800 nm spectral bands, respectively, in units of radiances, reflectance or at least ‘apparent reflectance’. CI values lie in the range of 0 to +2 but are typically between 0 and 1. The CI value would have been between 1 and 2 only if the reflectance signal were higher in the BLUE than in the RED. The idea behind this equation is to calculate the normalized difference between the relative higher reflectance which occurs in the red region and the minimal reflectance in the blue region. The subtraction of the normalized difference from 1 is suggested in order to create higher values for soils with high fines and organic matter contents. The calculated CI values for the field spectral measurements are presented in figure 2.

The CI can be applied to imagery acquired by any sensor which has BLUE, and RED or NIR bands. The most common and widely used source of information for this purpose are regular colour photographs or Landsat TM data. Similar results can be obtained using either the RED or the NIR band since the reflectance values are almost the same in the two bands. The decision as to whether to use either of these bands depends on the source image. RED band must be used when applying the index to a colour photograph while either RED or NIR values can be used when applying it to a Landsat TM image.

The index has been implemented on the colour photograph of Sede Hallamish site (figure 5). The results of the CI computation are presented in figure 7. One would notice that the same playa areas which originally appear in bright tones, here appear in dark tones, the sand dunes remain in bright tones (almost white), and biogenic crusted areas in different grey levels in-between.

Two cross sections of grey levels are presented in figure 8. One profile has been
generated from the red colour of the original aerial photograph (line A–A in figure 5). The other similar profile has been generated from the resulting CI image (line B–B in figure 7). Note that in order to reduce noise, the original curves have been smoothed slightly using the method of Fast Fourier Transform (FFT). From figure 8 it can be seen that by applying the CI, the overall image contrast has been enhanced almost to the entire dynamic range of the display device (0–255). Therefore the CI profile is much more sensitive to the ground features than the original profile. The most interesting issue in this figure is that the playa areas turn from relatively bright tones in the original spectrum to almost a black colour. Here the playa areas have the highest CI values (>0.725) and the lowest grey levels (0–70). The interdune crusts appear in intermediate grey tones. Their CI values are confined within 0.625–0.725 and the corresponding grey levels are 70–150. Lastly, the active dune sands which appear in bright tones in figure 7 have CI values of 0.55–0.625 and grey levels of 150–220.

Another example of implementing the proposed CI has been performed on
Figure 6. Grey level profiles of the red and blue bands of the original colour aerial photograph along the dune study area and the (BLUE/RED) ratio between them. Cross-section located is presented in figure 5.

Figure 7. Crust index (CI) image generated from the colour aerial photograph in figure 5.
Figure 8. Grey levels profiles of the red band of the original colour aerial photograph along the dune study area and after performing the crust index. Cross-section locations are presented in figure 5 and figure 7, respectively.

Figure 9. Landsat TM image of the study area (RGB = bands 3, 2, 1, after histogram equalization).
Landsat TM image using bands 1 (blue) and 3 (red). The source image is presented in figure 9 and the results in figure 10. This image covers geomorphological units (B), (C) and (D) (see §2). A simple first-order atmospheric correction was performed by the histogram adjustment technique (Jensen 1986). Dark-pixels over basalt hills located south-east of the study area were used as an estimate of the path radiance for the entire scene. Not many details can be noticed in the original Landsat image which looks dull and lacks contrast. But after applying the CI, the linear crescent-shaped dunes as well as the interdune areas are well distinguished. Dirt off-roads crossing the dunes, where vehicles trample the topsoil crust, can also be recognized.

4. Summary and conclusions

Data about soil crusts in arid lands contain considerable information with respect to the desert ecosystems since the soil crusts contribute to soil stability, soil build up, soil fertility, and to the soil water regime. Therefore, the absence or the existence and distribution of soil crust is an important information for desertification and climate change studies. It is also a highly valuable information for developing agricultural regions and/or infrastructures in arid environment.

This study shows the ability to detect and to map different units in a dune environment (such as active sands, crusted interdune areas and playas) by applying a spectral crust index. This index is based on a unique spectral feature of the cyanobacteria pigments which contributes to relatively higher reflectance values in the blue spectral band in comparison with the same substrate without crust. Another feature is the smooth, bright and homogeneous nature of the physical crust in the
playas. As a mapping tool the CI image is much more sensitive to the ground features than the original image.

The application of the proposed CI can be performed with imagery acquired by any sensor which contains the blue band. Most common are colour aerial photographs and Landsat TM images. The blue band has been recently recognized as an important band for different applications. Therefore, several other sensors such as the SPOT-VEGETATION, MOMS-2P, SeaWiFS and MODIS which will be available in the coming years can be used for crust mapping.

Acknowledgments

The research was supported by The Israel Science Foundation administrated by The Israel Academy of Sciences and Humanities, and partially by the International Arid Lands Consortium. The author would like to thank Dr Daphna Lavee for the vegetation survey data, Dr C. Ichoku, Mrs S. Gilerman, Mr E. Reuveni and Miss H. Schmidt for their help in processing the data. The soil texture analysis was conducted with the kindly help of Professor A. Yair and the pycobilin extraction with the help of Professor V. Sarafis. In addition, the author would like to thank the Minerva Center for Arid Ecosystem for giving me the opportunity to work in the Nizzana research site.

References


Development and implementation of spectral crust index over dune sands


