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The Effect of Microphytes on the Spectral Reflectance of Vegetation in Semiarid Regions

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The normalized difference vegetation index (NDVI), which is derived from satellite sensor images, is widely used as a measure of vegetation and ecosystem dynamics, change in land use, desertification, and climatic change processes on a regional or global scale. Surprisingly, in semiarid regions, relatively high values of NDVI were measured in landscapes where little, if any, photosynthetic activity of higher plants exists. We tested the hypothesis that the high NDVI values may be caused by the photosynthetic activity of microphytes (lower plants), consisting of mosses, lichens, algae, and cyanobacteria, which cover most of the rock and soil surfaces in semiarid regions. We found that the spectral reflectance curves of lower plants can be similar to those of the higher ones and their derived NDVI values can be as high as 0.30 units. We conclude that, in semiarid environments, the reflectance of lower plant communities may lead to misinterpretation of the vegetation dynamics and overestimation of ecosystem productivity.

SEMIARID REGIONS AND VEGETATION INDEX

Temporal and spatial variations of vegetation conditions and ecosystem dynamics can be monitored from satellite remote sensing images by utilizing spectral vegetation indices (VIs) (Perry and Lautenschlager, 1984; Cohen, 1991). Several VIs have been developed during the recent decades. Most indices are based upon a combination of the ratio between the red band, 600–700 nm, which corresponds to the region of maximum chlorophyll absorption, and the near-infrared band, 700–1100 nm, which corresponds to maximum reflectance of incident light by living vegetation. The most widely used index is the normalized difference vegetation index (NDVI) defined mathematically as $NDVI = [NIR - R] / [NIR + R]$, where R and NIR are the radiances or reflectances or at least "apparent reflectance" in the red and the near-infrared spectral bands, respectively (Rouse et al., 1974). The NDVI values lie in the range -1.0 to $+1.0$ where denser and/or healthier vegetation have higher positive values.

In humid regions and cultivated areas, empirical correlations have been found between satellite-derived NDVI and vegetation variables such as density, photosynthetic activity, green leaf biomass, leaf area, productivity, and carbon in standing biomass (Tucker, 1979; Curran, 1980; Holben et al., 1980; Asrar et al., 1984). Arid and semiarid regions are characterized by sparse vegetation cover within the soil matrix. The spectral reflectance of the soil background is different from that of vegetation. Consequently, several studies showed that it is difficult to extract information on vegetation properties when its cover is less than 30–40% (Colwell, 1974; Pearson et al., 1976; Huete et al., 1984; Elvidge and Lyon, 1985; Tueller, 1987; Smith et al., 1990). This is due to the spectral dominance of the background soil and rocks. However, surprisingly, relatively high values of NDVI were reported in arid and semiarid regions for areas where little, if any, photosynthetic activity of higher plants exists (Holben, 1986; Townshend and Justice, 1986; Tucker et al., 1985). These areas were denoted as "desert artifacts" (Huete and Tucker, 1991).

A question arises as to the sources of the unexpectedly high NDVI values in semiarid regions. We tested the hypothesis that the high NDVI values are caused by the photosynthetic activity of lower plants that, in absence of higher plants, cover most of the rock and soil surfaces in semiarid regions. We measured the

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spectral reflectances of a diverse array of microphytic communities. Microphytes (= small plants) is a common name for mosses, lichens, fungi, algae, cyanobacteria (= blue-green algae), and soil bacteria (West, 1990). Principally, the existence of a few microphytic communities (such as algae) seem out of place in the desert environment since they are usually associated with plenty of water and often found in water bodies. However, they also appear in other strange and extreme conditions (Evenari et al., 1982).

The research was conducted in the Negev desert of Israel on three pedological / lithological units: sand dunes, loess soil plains, and sedimentary (carbonatic) rocky terrain. Measurements on different substrates is important because the abundance and distribution of microphytic species in the Negev change in relation to the nature of the substrate and the moisture regime (i.e., either rainfall on soil or dewfall on rocks).

The microphytic soil crust community over sand dunes consists mainly of cyanobacteria (Danin et al., 1989). The cyanobacteria structure is similar to that of bacteria, but their photosynthetic mechanism resembles that of the green algae. The cyanobacteria have only chlorophyll *a*. Some of them are able to fix atmospheric nitrogen that is needed for proteins. All these features make it possible for them to occupy an ecological niche in the desert where others cannot live.

Together, epilithic and endolithic lichens (which thrive above and below the upper rock surface, respectively) are the most common component of the rocky terrain (Shachak et al., 1987). Lichens result from the symbiosis between fungi and cyanobacteria or green algae. The algae benefit in part because of the protection offered by the fungi against environmental stresses. The photosynthetic algae produce organic materials from carbon dioxide, water, and other substances in the air, water, and rock; some of these organic compounds are then used by the fungi. Sometimes the fungi benefit when the partner is constituted by cyanobacteria which fix atmospheric nitrogen. Symbiosis of this nature gives the lichens the ability to settle in the most extreme habitats where neither the fungi nor the algae could exist alone. In many hot and cold deserts and high mountains they are the dominant or the only vegetational elements. Some of them can tolerate temperatures of over 80°C and remain photosynthetically active, and can continue to increase their dry matter even at temperatures as low as −10°C (Evenari et al., 1982). Twenty-seven lichen species were found on nine kinds of calcareous substrates in the Negev desert (Isarov and Isarova, 1995).

Different types of microphytic crusts are also very common on the loess soils (West, 1990): cyanobacteria crust dominates in regions where there is less than 100 mm of rain, soil lichens in regions of 100–200 mm of rain, and mosses in regions of 200–300 mm. Mosses are small plants (1–50 mm) with simple anatomic structure (nonvascular plant). Water and minerals are absorbed directly and rapidly throughout their surface. Mosses are attached to the substrate by elongate single cells or filaments of cells called rhizoids, which serve only to anchor the plants. Their photosynthetic system is similar to that of higher plants, with chlorophyll *a* and *b*. Mosses contribute to the crust stability because of their rhizoids that are used as skeleton. About 28 species of mosses have been found in the Negev desert. Their ability to tolerate dry seasons, because of their structure and ecophysiological adaptation, which enable them to lose about 70% of their body water, makes them able to adapt to desert conditions. A few minutes after rewetting they revert to photosynthetic activity.

An earlier article dealing with the reflectance spectra of microphytic soil crusts in semiarid regions was recently published by O'Neill (1994). In that article reflectance spectra obtained from the GER IRIS spectroradiometer were used to study vegetation cover and microphytic crusts on a variety of soils. Noticeable differences upon wetting of microphytic crusts were observed using this method. The large percentage cover of microphytic crust and litter in ungrazed semiarid rangelands was noted.

The annual precipitation in the Negev ranges spatially between 25 mm and 350 mm with about 40% annual variation in rainfall amounts. The climatic gradient is of the order of 100 mm rainfall over 50 km distance. The number of rainfall days per annum varies between 5 and 40. Special attention should be given to the high amount of dewfall in the northern Negev. The average number of dewfall nights is about 200 per year, mainly from June to November, the driest months in terms of rainfall. The total water produced annually by dew can reach approximately 40 mm, although the amount formed per dew night is small (Evenari et al., 1982; Zangvil and Druian, 1980). Microphytes in the Negev Highlands may photosynthesize 200–600 h annually using the moisture from dewfall (Danin and Garti, 1983). The mean annual air temperature is 18°C, and the annual mean relative humidity is 54%.

METHODOLOGY

The spectral characteristics of the microphytic crusts was studied *in situ* in the field and in the laboratory. In the field, we used the Li-Cor LI-1800 field-portable spectrometer (LI-COR, 1989). The instrument was fixed to 2 nm wavelength spectral resolution increments between 400 nm and 1100 nm and 15° field of view (FOV). It was hand held at about 1 m heights, at nadir above the ground or vegetation. The reflectance is calculated by relating the target radiances to the downwelling irradiation as measured by a cosine-corrected receptor.

In addition, rock, soil, and sand spectra were measured in the laboratory by using two types of spectrometers. First, the Li-Cor LI-1800 was applied with the same basic configuration (spectral resolution and FOV) as in the field, but, here, the detector head was installed on a tripod about 1 m above the sample, at nadir. The illumination source, a 1000 W quartz halogen lamp, was positioned at a 45° zenith angle, approximately 1 m away from the sample. The samples were laid on a black-coated board to minimize external reflectance or backscatter. Spectral measurements of a halon reflectance panel were obtained at the beginning of each data set, to be used as reference for the bidirectional reflectance factor (BRF) calculations. The BRF was determined by dividing each sample spectrum by the halon spectrum collected within the shortest time interval between those measurements so as to avoid light oscillation effects. Each spectrum is an average of four spectra. The rock samples, which are relatively rougher than the soil and sand samples, were rotated 90° between scans. Laboratory measurements with the field spectrometer are more likely to have random noise especially below 500 nm and above 1000 nm. The presence of the random noise in these portions of the spectra was minimized using two average filters consisting of moving windows of five and three points, sequentially.

For the rock samples we used the Beckman DK-2A spectroreflectometer. Its optical path and method of measurement of transmission and reflection are described in Porter (1967). The bandwidth of measurement is from 290 nm to 2600 nm. The integrating sphere collects all light reflected alternately between the reference $BaSO_4$ surface and the test material. Both reference and test material are positioned against the outside surface of the hollow sphere coated on the inside with ultrapure $BaSO_4$. Light enters from openings on the opposite side of the hollow sphere to strike the reference and test surfaces. Reflected diffuse and specular light is measured simultaneously by a lead sulfide detector in the 700–2600 nm range and by a photomultiplier detector in the 290–700 nm range. A prism breaks the light from the tungsten and deuterium sources and a variable slit maintains a constant beam energy which is compared with an internal constant reference standard. The beam width is typically about 0.1–1 mm in width and about 1 cm high as the machine automatically scans through the spectrum.

RESULTS

The Sand Dune Environment

Spectral reflectance curves of dry sand, dry and wet cyanobacteria soil crust, and *Artemisia monosperma* are presented in Figure 1. These field measurements were obtained almost simultaneously from an area with about 100 mm mean annual rainfall, using the Li-Cor LI-1800 spectrometer. *Artemisia monosperma* gives a higher typical vegetation spectral reflectance curve: relatively small peak in the green region, dips in the blue and red regions due to chlorophyll absorption, and relatively high plateau in the NIR region due to leaf structure reflectance. The vegetation reflectance is much lower than those for sand and crust. We obtained almost identical curves for *Retama raetam*, *Lycium schweinfurthii*, *Stipagrostis scoparia*, and other species of sand dune shrubs (Pinker and Karnieli, 1995). The cyanobacteria crust, which consists mostly of *Microcoleus vaginatus* accompanied with *Scytonema*, *Schizothrix*, *Calothrix*, *Chroococcidiopsis*, *Nostoc*, and *Phormidium* (Danin, 1991), produces spectra that are somewhat lower than the sand dune spectra. Both dune and crust spectra have a typical soil curve shape: relatively low in the blue region and increasing gradually towards the near-infrared region.

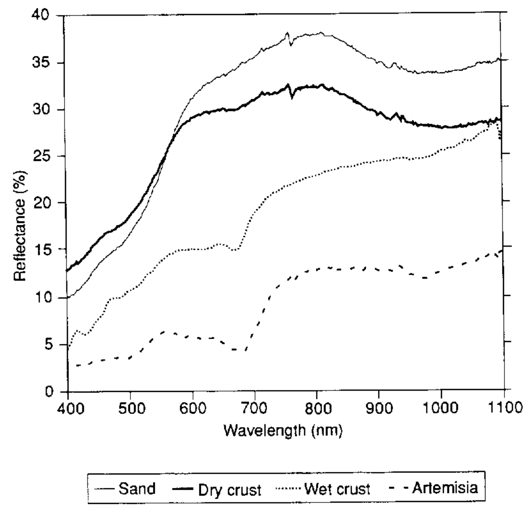


Figure 1. Spectral field measurements of uncrusty, dry and wet microphytic crusty sand dune and typical vegetation in the western Negev, on 2 October 1992.

When the cyanobacteria crust is wet, it turns green, as demonstrated in Figure 2. Consequently, a notable change in the reflectance curve of the cyanobacteria crust occurs (Fig. 1): its reflectance is lower than that of the dry crust and exhibits a significant dip in the red region due to the photosynthetic activity of the cyanobacteria. This spectral feature produces a much higher NDVI value for the wet crust than for the dry crust (0.22 vs. 0.08 units, respectively).

The difference between the dry and wet spectra represents the response of lower plants to the frequent changes in water availability, typical of deserts. Microphytes are poikilohydrous plants, that is, they are physiologically and ecologically active when their substrate is

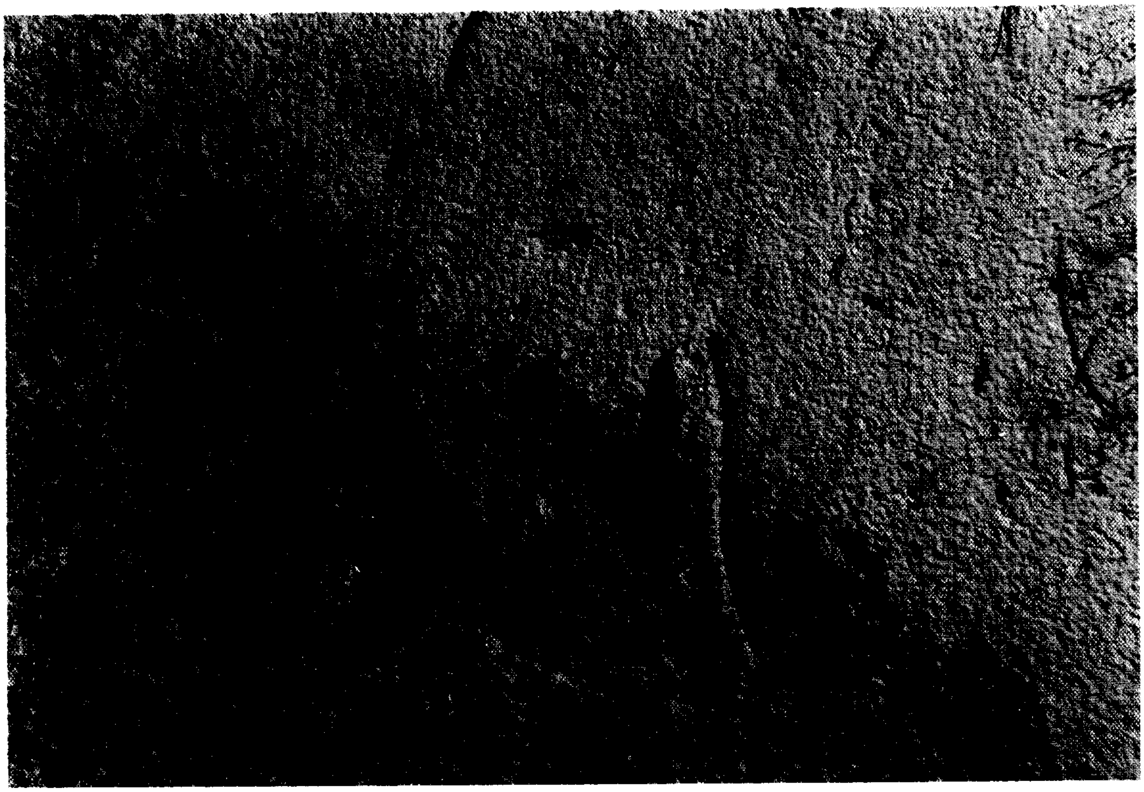


Figure 2. Dry (upper right) versus wet (lower left) cyanobacteria crust.

moist and become dormant when it is dry. A few minutes after wetting, they start respiring, and if light is available, they revert to full photosynthetic activity. On the other hand, they can persist under extremely dry conditions till water becomes available. Their hydration–dehydration cycles can be repeated innumerable times (Friedmann, 1971).

The Loess Environment

Samples of the most common microphytic communities on top of loess soil are shown in Figure 3: a) a community dominated by cyanobacteria (mainly *Microcoleus vaginatus*, *Nostoc punctiforme*, and *Chroococcus* sp.); b) a community dominated by soil cyanophilous lichen (*Collema* sp.); c) a community dominated by two species of moss (*Aloina bifrons* and *Crossidium crassinerve var. loevipilum* from a south-facing slope; and d) a community dominated by the same two species of mosses, but in different proportions, from a north-facing slope. In addition, the spectra of the loess soil, with no crust, is also presented, as a reference. The respective laboratory spectral reflectance curves are presented in Figure 4. As expected in the northern hemisphere, the south-facing slope is drier than the north-facing one. The spectra were measured in the laboratory, using the Li-Cor LI-1800 spectrometer.

All the microphytic soil crust samples had been collected by scraping the soil surface to 1 cm depth from an area of 200 mm mean annual rainfall. The samples were collected in January 1993; thus, they represent the field conditions (natural moist) during the wettest month of the year. At that time, it was observed that the annuals had not yet germinated and the perennials had hardly sprouted; nevertheless, the microphytic community exhibited peak biomass (Fig. 5). The crust-free soil has a convex shape of curve typical of soils (Fig. 4). In contrast, the spectra of the microphytic soil crusts, although generally characterized by the same convex shape, show a significant dip between 600 nm and 700 nm, which corresponds to the region of chlorophyll absorption. The moss community from the north-facing slope has almost a typical vegetation curve. Calculations show that the soil NDVI is 0.08 units, but the cyanobacteria, lichens, south- and north-hillslope facing mosses communities give NDVIs of 0.10, 0.14, 0.19, and 0.30 units, respectively.

These four communities represent changes in microphytic community structure along a soil moisture gradient with the cyanobacteria on the dry end and the mosses on the north-facing slope on the wet end. The higher the soil moisture, the higher the absorbance features in the reflectance spectra and the higher the NDVI values. We suggest that the variation in the spectra and the NDVI values of microphytic communi-

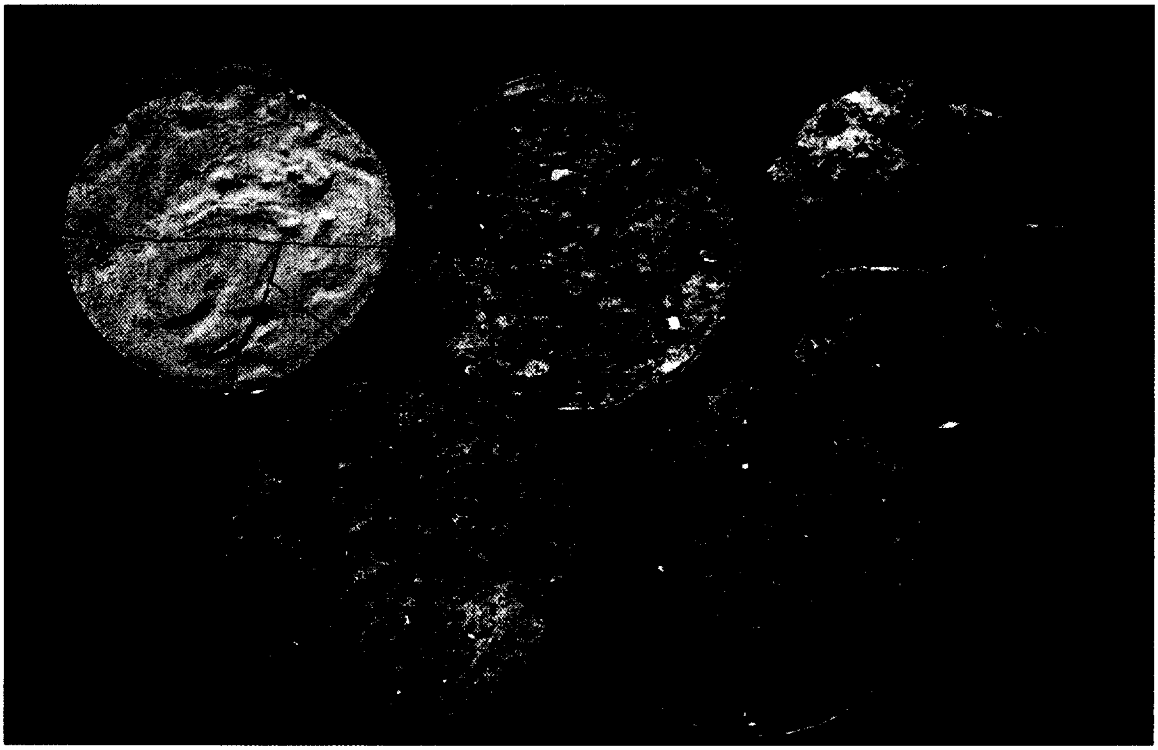
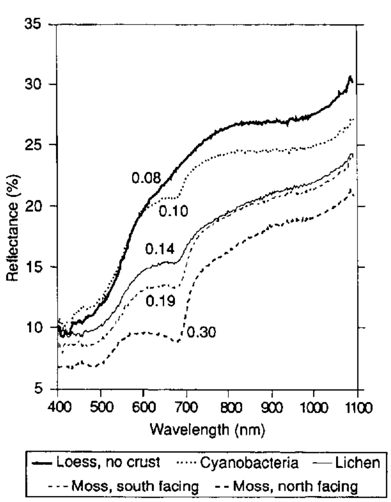


Figure 3. Different microphytic communities in the loess environment. Upper samples from left to right: bare loess soil; cyanobacteria; lichens. Lower samples from left to right: mosses on south facing hillslope; mosses on north facing hillslope.

ties is caused by: 1) differences in the microphytic community structure, that is, species composition, and 2) the variation of each species abundance. Community structure and species abundance reflects the spatial variability in soil moisture. On a local scale, moisture variability is mainly due to slope direction, while, on a regional scale, it is mainly due to changes in rainfall amount.

Figure 4. Spectral laboratory measurements of different microphytic communities on loess soil, sampled on 7 January 1993, with their respective NDVI values.



The Rocky Terrain Environment

Turonian limestone covered by endolithic lichens (*Caloplaca alociza*), sampled in an area of about 100 mm of mean annual rainfall, is demonstrated in Figure 6. This type of lichens live just beneath the surface of the rock. Feeding snails cut the white grooves into the rock which form a "jigsaw puzzle" pattern (Shachak et al., 1987; Jones and Shachak, 1994). Laboratory reflectance measurements of similar samples using the Beckman Model DK-2A spectroreflectometer are presented in Figure 7. Each rock sample was measured four times: measurements of dry samples of the upper and bottom surfaces of the rock and later of wet samples of the same surfaces. The upper surfaces were covered with the lichens while the bottom surfaces were lichen-free and thus were used as a reference. In Figure 7 it is shown that the bottom dry spectra has the highest reflectance. The upper dry spectra represents a relatively similar curve, somewhat lower, and with a slight dip in the red region. When wet, the bottom spectra have the same shape as the dry ones but with a stronger

Figure 5. Overview of the south facing hillslope in the loess environment.

absorbance value in the visible–near-infrared regions. Also, the water absorption bands in the mid-infrared region are clearly evident. Finally, the upper wet spectra has the lowest reflectance curve. Here, this curve has a significant dip between 600 nm and 700 nm due to the photosynthetic activity of the lichens. The NDVI values of the bottom wet and dry spectra, as well as the upper dry one, range between 0.09 units and 0.15 units. However, the NDVI value of the upper wet one reaches 0.30 units.

As in the case of the soil crust, the rocky microphytic community responds to changes in water availability. Lichens, like cyanobacteria, are poikilohydrous plants. They become active and turn green (Fig. 6) when dew is deposited on rocks during nights and early mornings and turn dormant after the dew evaporates. This rapid response to dew enables them to photosynthesize for a few hours during about 200 days both in the winter and summer in the Negev.

In order to study regional changes in the reflectances and NDVI of lichenized rocks we sampled limestone rocks of the same geological formation (Upper Turonian age) along a 210 km transect in Israel, from the hyperarid zone (mean annual rainfall of 25 mm) to the subhumid zone (mean annual rainfall of 350 mm) (Fig. 8). Laboratory spectral measurements of the samples show that the NDVI values of the dry samples vary relatively little along the entire transect (0.08–0.13 units). However, a notable change, forming a steplike shape at the area of about 90 mm of rainfall, was found in the wet samples where the NDVI values range from 0.18 to 0.32 units. In the drier region of the transect with less than 90 mm of rainfall where the lichens cover is relatively small, NDVI values are around 0.20 units. Yet, in the wetter region where the lichens cover as epiliths and endoliths is high, approaching 100%, the NDVI values are around 0.30 units. The dramatic increase of the NDVI values in the wetter region is due to the vast cover of lichens which is obviously affected by a higher rainfall amount, but also wet by a much better dewfall regime. The reason for the importance of the dew is mentioned earlier: In the wetter region the number of rainfall days per annum is relatively low, between 5 days and 40 days, whereas the average dew nights is about 200 per year. A steep rim, 300 m high, which exists between the wetter and the drier regions, blocks rainfall and dewfall migration to the drier region.

MICROPHYTIC COMMUNITIES AND THE SATELLITE'S SENSOR SIGNAL

Our study shows that a slight photosynthetic signal exists when the microphytic crusts are dry, but a notable signal occurs when they are wet. When wet, their spec-

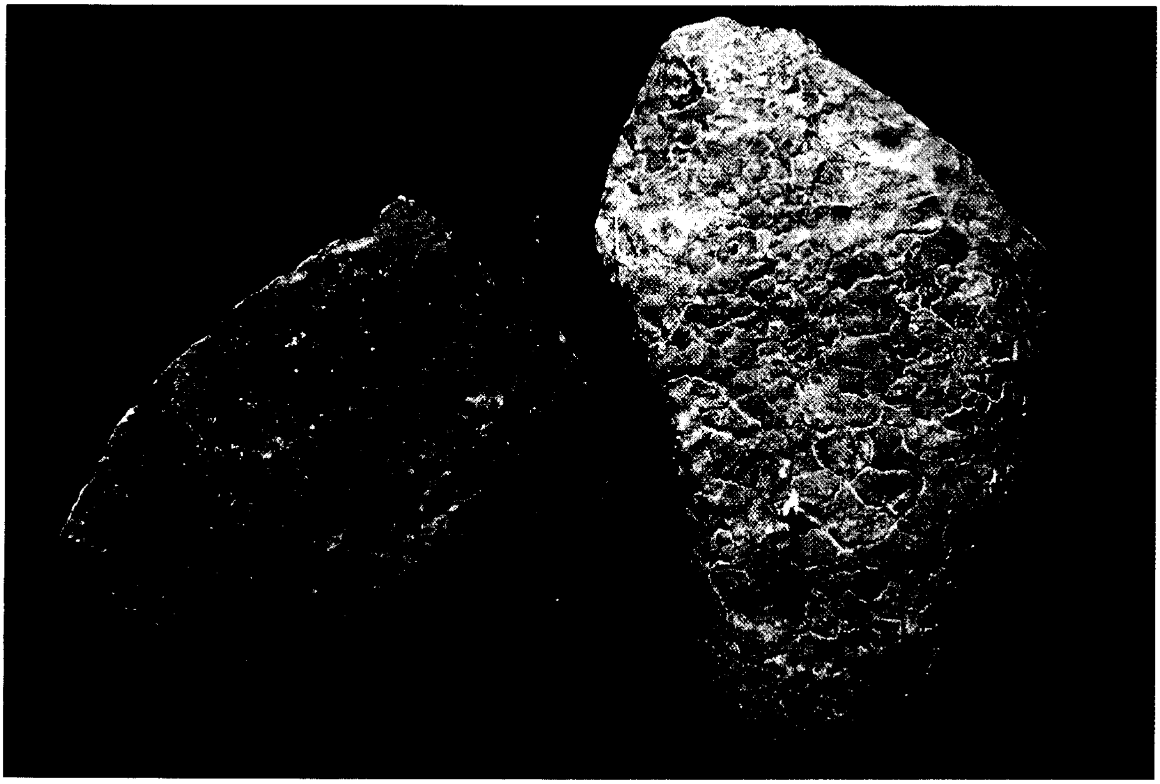
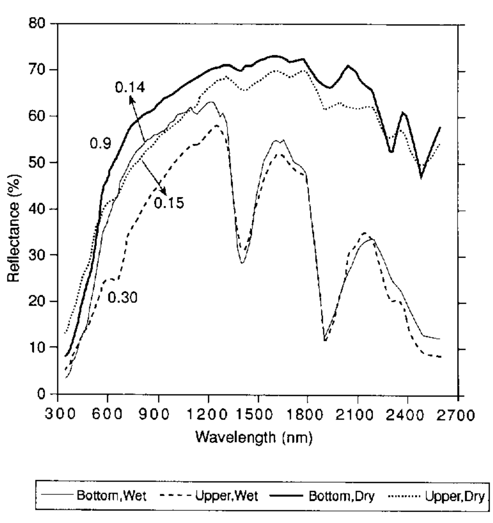


Figure 6. Dry (right) versus wet (left) Turonian limestone rocks with endolithic lichens.

tral reflectances are relatively lower than when they are dry, and their NDVI value rises up to 0.30 units. Consequently, under semiarid conditions where higher vegetation is sparse and covers less than 30% of the surface, most of the satellite signal from surface reflectance are produced by the microphytes which may cover up to 100% of the area. The similarity in the spectral response of higher and lower plants may therefore lead to misinterpretation of the NDVI values, such as overestimation of the vegetation biomass or productivity.

Figure 7. Spectral laboratory measurements of different surfaces of Turonian lichenized limestone rocks with their NDVI values.



Microphytes activity can affect our NDVI interpretation during both wet and dry seasons. Microphytes in soil respond quickly and reach their peak activity at the beginning of the rainy season when higher plant activity is still very low. The satellite signals taken during this period are generated mainly by the microphytic soil crust communities. Microphytes on rocks are active in the mornings up to 200 days / year when dew and fog provide moisture. Satellite signals obtained from rocky deserts during the summer mornings may be mainly affected from the rock-dwelling microphytic communities. Therefore, we suspect that the soil-related "desert artifact" areas observed over portions of the Sahara desert, Egypt, and the Arabian peninsula can be explained, in part, by photosynthetic activities of microphytes.

The problem is even more severe due to the technique used to compose the global vegetation maps in the study of vegetation dynamics. The "maximum value composite" (MVC) technique is used to eliminate the effect of clouds and haze from vegetation maps (Holben, 1986). Its basic steps are: a) calculation of the NDVI for each daily image; b) composition of the NDVI values

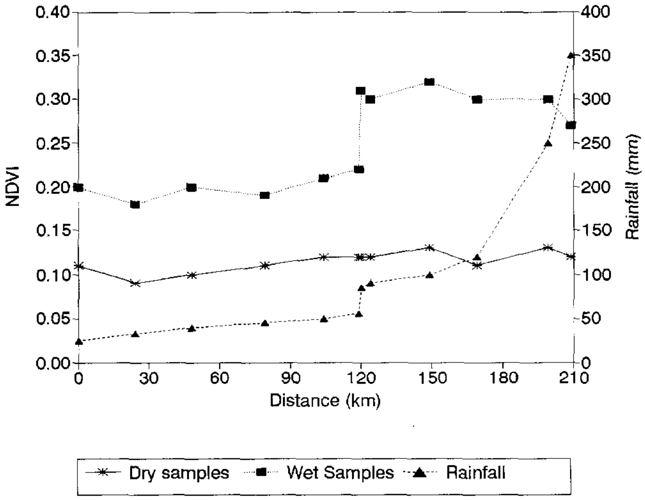


Figure 8. NDVI gradient of dry and wet Turonian lichenized limestone rocks along the climatic gradient of Israel.

for each individual pixel in the image with those in other images; and c) keeping the maximum NDVI value over the entire compositing period. Here the maximum NDVI value from a period between 7 days and 30 days is used to represent the whole period. The quick response of microphytes to moisture coupled with the maximum value composite will further enhance the effect of the microphytes on remote sensing of vegetation.

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