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Analysis of the temporal and spatial vegetation patterns in a semi-arid environment observed by NOAA AVHRR imagery and spectral ground measurements

H. SCHMIDT and A. KARNIELI*

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

Abstract. The borderline between Israel and Sinai is characterized by a sharp contrast that is caused by the low spectral reflectance on the Israeli side (Negev desert) and the high spectral reflectance on the bare Egyptian side (Sinai desert). This contrast across the political border has been discussed in many publications over the last two decades. In this study, satellite images acquired by NOAA Advanced Very High Resolution Radiometer (AVHRR) over a time period of 3 years (June 1995 to June 1998) were analysed. In addition, extensive field studies were carried out on the Israel side of the border. The current research shows that the reflectance values in Sinai seem to be quite stable over the entire year, however reflectance values in the Negev show a significant difference between the dry and the rainy seasons. Comparison between the AVHRR-derived Normalized Difference Vegetation Index (NDVI) values and rainfall data from the Negev shows that the highest AVHRR-derived NDVI values occur a few weeks after the main rainfall. Field observations, based on spectrometer measurements of different surface components (bare sands, biological soil crusts, annuals, and perennials) and estimation of vegetation cover on the Israeli side of the border, show that the peak NDVI of the perennials occurs at the same time as the satellite observed peak. The spectral difference between both sides of the border during the dry season is caused by the dense cover of the higher vegetation and the biological soil crusts and by the photosynthetic activity of perennials during the dry season. The highest difference between both sides during the rainy season is caused by the photosynthetic activity and vegetation cover of the annuals and perennials.

1. Introduction

Arid and semi-arid environments are characterized by sparse vegetation cover. One of the most distinct features of this environment that affects the plant growth is the seasonal and year-to-year fluctuation of rainfall. In arid ecosystems with a single rainy season, there is usually a short growth period followed by a prolonged dry spell of considerable reduction in the amount of green plant material. It is well known that different vegetation components (biological soil crusts, annuals, and perennials) and bare surfaces respond differently to rainfall. Time-series analysis of

*Corresponding author; e-mail: karnieli@bgumail.bgu.ac.il

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data enables observing seasonal and annual trends in vegetation cover, and helps to find out the reason for spectral variability. Multitemporal satellite sensor data have been shown to be useful in monitoring the plant phenology or the rainfall condition that are reflected in vegetation phenologic cycles (e.g. Townshend and Justice 1986, Justice and Hiernaux 1986, Justice *et al.* 1991, Lambin and Strahler 1994, Prince *et al.* 1995).

The Advanced Very High Resolution Radiometer (AVHRR) operated by the National Oceanic Atmospheric Administration (NOAA) with a high temporal resolution of about 1 day plays a significant role in monitoring regional and global processes. The most important AVHRR-derived product for ecological applications is the Normalized Difference Vegetation Index (NDVI) developed by Rouse *et al.* (1974):

$$\mathrm{NDVI} = (\mathrm{NIR} - R)/(\mathrm{NIR} + R) \quad (1)$$

where R is the reflectance in the red channel and NIR is the reflectance in the near-infrared channel of the NOAA AVHRR sensor. This index shows positive correlation with photosynthetic activity, vegetation cover, biomass, and Leaf Area Index (LAI) (e.g. Holben 1986, Chilar *et al.* 1991, Ehrlich *et al.* 1994, Prince *et al.* 1995). It is demonstrated that multitemporal NDVI images are useful for analysing spatial vegetation patterns and for assessing vegetation dynamics (e.g. Justice *et al.* 1985, Justice and Hiernaux 1986, Gutman 1991, Townshend and Justice 1986). Using NDVI images derived from AVHRR data, vegetation-cover classes can be separated in multitemporal space according to their phenological variations (e.g. Justice *et al.* 1985, Tucker *et al.* 1985, Tucker 1986, Hobbs 1995, Ehrlich *et al.* 1994). Vegetation indices and their information can be related to long-term meteorological events (Justice *et al.* 1985, Hielkema *et al.* 1986, Townshend and Justice 1986), plant species distribution (Tappan *et al.* 1992, Mora and Iverson 1997) and changes in vegetation cover (Justice *et al.* 1985, Justice and Hiernaux 1986).

NDVI values derived from AVHRR observations in a semi-arid environment have been found to be closely correlated with rainfall (Hielkema *et al.* 1986, Tappan *et al.* 1992, Maselli *et al.* 1993). In many arid landscapes, rainfalls are irregular and unevenly distributed temporally and spatially. The peak of NDVI observations for an area may not coincide with the timing of the physical maturity of the herbage plants in that area (Samson 1993). The NDVI–rainfall relationship is a sensitive indicator for the inter-annual variability of rainfall, and the timing of NDVI response to rainfall was studied by Nichelson *et al.* (1990). The results of that study show that there is a good relationship between rainfall variations and NDVI on seasonal and inter-annual time scales. The best association is generally between NDVI and a 3-month average of rainfall in the concurrent and two previous months. This delayed response suggests that NDVI is a better indicator of vegetation growth and soil moisture than of rainfall (Nichelson *et al.* 1990, Nichelson and Farrar 1994).

The major difficulty involved in the use of NDVI lies in several environmental factors that can affect the relation between the vegetation index and total biomass production. These include terrain topography, soil types and soil moisture, different vegetation associations, and more (e.g. Huete and Tucker 1991, Farrar and Nicholson 1994, Leprieur *et al.* 1996). Lozano-Gracia *et al.* (1991) studied the regional biomass–soil relationship using NOAA AVHRR based NDVI values for two growing seasons in the midwestern USA. The results of this study indicate that land-cover types, soil texture, and soil water-holding capacity have an important effect on vegetation biomass changes as measured by AVHRR data. Kremer and Running (1993) assessed the ability of AVHRR/NDVI data to record intrabiome variability of phenological and structural characteristics of grass and shrub communities in a semi-arid ecosystem. The authors found out that the primary limitation of using AVHRR data to delineate among vegetation communities within a single biome is the coarse spatial resolution of the data that might be greater than the inherent topographic and vegetation variability over regional scales.

The objective of this paper is to investigate the possibility of remote monitoring temporal and spatial variation of reflectances across the Israel–Egypt border and the impact of the seasonal variation of the higher and lower vegetation on this phenomenon. Field measurements were only possible on the Israeli side of the border. The comparison of Egyptian and the Israeli side of the border is limited on the satellite measurements. This contribution constitutes one of the first attempts to study the seasonal variation of the vegetation in the Negev on the basis of 3 years of observations using radiometrically- and atmospherically-corrected NOAA AVHRR images and field measurements acquired during a 2-year period.

2. Study area

The borderline between the Negev and Sinai is characterized by a sharp contrast that is caused by the low spectral reflectance in the Negev desert and the high spectral reflectance in the Sinai desert. This phenomenon can be observed in all spectral bands including the thermal and microwave regions. This contrast along the political border has been discussed in many publications over the last two decades since launch of the first Landsat Multi-Spectral Scanner (MSS) sensor (e.g. Otterman 1974, 1977, 1981, Otterman *et al.* 1975, Otterman and Fraser 1976, Danin 1983, 1991, Otterman and Tucker 1985, Danin *et al.* 1989).

Different explanations exist about the reason for this sharp contrast (Karnieli and Tsoar 1995, Tsoar and Karnieli 1996, Otterman 1996). Karnieli and Tsoar (1995) present spectral ground measurements for different surface components (sands, biological soil crusts and shrubs) and analysed an aerial photograph from this area. They found out that a significant spectral contrast exists between bare sands and biological soil crusts. The same authors analysed three Landsat MSS images spanning a time period of 5 years (Tsoar and Karnieli 1996). Based on these a gradual decrease in the brightness of the Negev between 1984 and 1989 was observed in the visible and near-infrared bands of the MSS sensor. The authors conclude that the well-known contrast between both sides is not a direct result of vegetation cover but is caused by the biological soil crusts in the Negev, and a lack of this crust in Sinai, due largely to anthropogenic activity (of men and animals). Karnieli (1997) developed a Crust Index (CI) and applied it for this region. The Negev shows a high density of biogenic crust cover in contrast to Sinai with almost no biogenic crust cover.

Otterman (1996) has rejected biological soil crusts as responsible for the low spectral reflectance in the Negev. The author sees the cover of higher plants and their shadowing effects in producing the spectral contrast. Ground observations show individual desert shrubs as much darker than the soil. The sparse cover of these higher plants tend to merge at elevated view directions, producing a uniform darkening of the entire area in satellite images with low viewing angle and low sun, respectively. Note that most of the above-mentioned studies are based on the analysis of a few satellite images, mainly Landsat MSS.

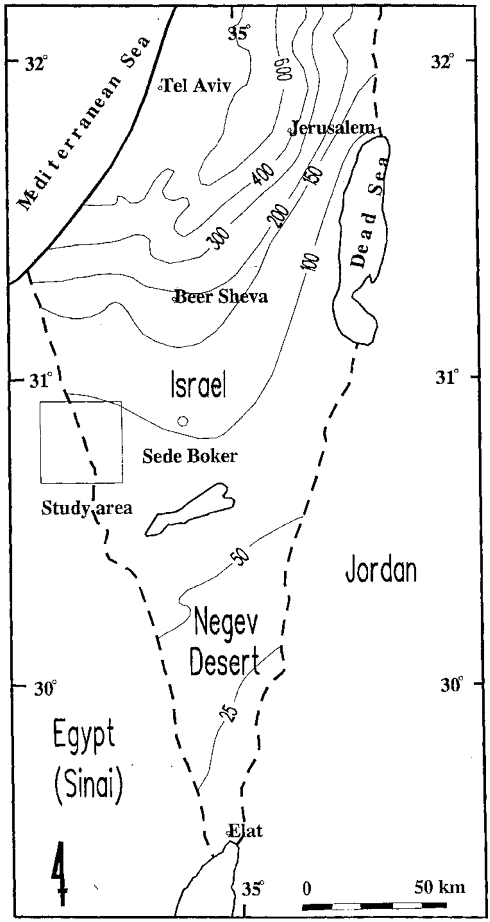

Figure 1. Location of the study area and the rainfall distribution over the southern part of Israel.

The study area (Sede-Hallamish), located in the north-western Negev desert of Israel (figure 1), is a sandy environment that represents the eastern extension of the Sinai sand fields from the geomorphological and lithological points of view (Tsoar 1990, Tsoar and Moller 1986, Tsoar *et al.* 1995). The area consists of longitudinal dunes with wide interdune corridors.

The mean annual precipitation for the study area is about 100 mm concentrated during the rainy season (from November until March). The amount, intensity, and distribution of rainfall vary considerably from year to year. The rainfall in Sede-Hallamish was 176 mm in 1994/95, high above the annual average. The 1995/96 rainy season was very dry and had a total rainfall of 32.3 mm much below the annual average. The two rainy seasons in the next 2 years (1996/97 and 1997/98) were represented by around average annual rainfall with 79.3 mm and 85.1 mm, respectively. In the 1996/97 rainy season, the rainfall distribution was uneven, concentrating mainly within 1 month (January). The 1997/98 rainy season had two major rainfall months (January and February).

The study area is represented by natural vegetation consisting mainly of sparse higher vegetation (e.g. *Anabasetum articulatae*, *Artemisia monosperma*, *Thymelia hirsuta*, *Retama raetam* and *Stipagrostis scoparia*). The slopes of the dunes as well as the interdune corridors are covered by biological soil crusts of mainly cyanobacteria (Karnieli and Tsoar 1995, Karnieli 1997). The cyanobacteria communities consist of *Microcoleus vaginatus* accompanied by *Scytonema*, *Schizothrix*, *Calothrix*, *Chroococcidiopsis*, *Nostoc* and *Phormidium* (Danin 1996). In this work, not much attention has been paid to differentiate between different species of desert plants. However, the vegetation has been gathered into three categories: perennials, annuals, and lower plant communities consisting of biological soil crusts.

3. Methods

3.1. *Spectral ground measurements*

In the Negev, reflectance values were measured in the field between 400 and 1100 nm wavelength in 2 nm increments, using a LICOR spectrometer (LI-COR 1989). Reflected radiation was measured with a 15° field-of-view from a height of about 1 m. The spectral reflectance was calculated by relating the target radiances to the downwelling irradiation as measured by a cosine-corrected receptor. Different vegetation components (perennials, annuals, and biological soil crusts) and various bare surfaces (sands and playa) were measured in the study area. Spectral measurements were carried out during 2 years parallel to NOAA AVHRR observation. Frequent measurements were taken during the rainy season while the prolonged dry season is represented by only a few measurements, since no significant change in vegetation and soil was observed.

The relative contribution of percentage of vegetation cover was estimated during the rainy and dry season of 2 years (1997 and 1998) by using the McAuliffe method (McAuliffe 1990). This method allows rapid estimates of density and cover of perennial vegetation in arid environments. Within the test site, points were selected as centres of circular plots. The plots used had a radius of 18 m (area = 1024 m^2). All shrubs with different diameters were counted and the percentage cover was estimated based on a logarithmic formula. The plots were well distributed along a transect from one dune to another in order to represent the area appreciably. The annuals were counted in 1 m^2 plots along the same transect. Table 1 lists the vegetation cover (%) in the Negev study area based on the McAuliffe method.

In order to estimate the overall spectral signal reflected from different ground components in a digital satellite image, the Linear Mixture Model was used (Ichoku and Karnieli 1996). The basic physical assumption of the model is that there is no significant amount of multiple scattering between the different cover types. Consequently, the signal measured by a sensor on a given pixel can be considered

Table 1. Percentage of vegetation cover based on the McAuliffe method.

	Cover of perennials (%)	Cover of annuals (%)	Cover of biogenic crusts (%)
March 1997	13.7	14.4	60
June 1997	13.7	1.6	60
December 1997	13.7	0.8	60
March 1998	13.7	27.3	60

as the sum of the signals received from each of the constituent cover components weighted by their respective areal proportions within the pixel (Ouaidrari *et al.* 1996). Therefore, for a given spectral band, the expected reflectance value R of a mixed pixel can be expressed by the following formula:

$$R=\sum_{i=1}^{n} P_i \rho_{ij} \tag{2}$$

where P_i is the relative contribution or fraction of component i and ρ is the spectral response of component i in waveband j. In the current study, the linear mixture model was applied for the spectral ground measurements of all surface components. The purpose was to mix the spectral responses according to their percentage cover in order to simulate their responses in the NOAA AVHRR red and NIR spectral bands. It was assumed that the weighted sum of the measured spectral response of the different surface components is equal to the integral spectral response of individual pixels as observed by NOAA AVHRR in the Negev study area.

3.2. *Satellite data processing*

The study is based on NOAA AVHRR satellite data that were acquired in High-Resolution Picture Transmission (HRPT) format in Sede Boker (Israel, the Negev Desert). NOAA-14 AVHRR images of Israel were obtained for the three-year time period from June 1995 to June 1998. Figure 2 shows a subset of a NOAA AVHRR image of the studied region. The geometrical distortion introduced by the extreme scan angle was reduced by limiting the use of the images with a satellite zenith angle of 30°. Beside, only cloud-free images were used in this work.

The correction procedure was divided into three parts: radiometric correction, atmospheric correction, and the geometrical correction. The process of data in the visible and the NIR channels is based on post-launch calibration coefficients, suggested by the calibration group at the NOAA/NESDIS Office of Research Application (Rao and Chen 1996). Atmospheric correction of the top-of-atmosphere (TOA) reflectances was carried out using the 6S algorithm. This computer code (6S—Second Simulation of the Satellite Signal in the Solar Spectrum) allows the estimation of the solar radiation backscattered by the Earth-surface–atmosphere system, as it is observed by a satellite sensor (Vermote *et al.* 1997). For successful atmospheric correction, the code requires estimates of the water vapour, aerosol, and ozone contents in the atmosphere. Estimates of total precipitable water and aerosol optical thickness of the atmosphere were obtained from an automatic tracking sun photometer (CIMEL), installed in Sede Boker, about 50 km apart from the study area. Ozone content in the atmosphere is based on climatology derived from the Total Ozone Mapping Spectrometer (TOMS 1993) onboard the Nimbus-7 spacecraft between 1987 and 1993. For images where data of atmospheric condition were not available, only the ozone content of atmosphere was corrected.

The images were geometrically corrected to a master image using ground control points and applying a nonlinear second order transformation. The accuracy of the correction lies at the subpixel level. The NDVI (equation 1) was calculated from the surface reflectance values for all AVHRR images.

NDVI composites were made on a monthly basis using the maximum value composite (MVC) method (Holben 1986). This technique reduces directional reflectance and off-nadir viewing effects and minimizes sun-angle and shadow effects.

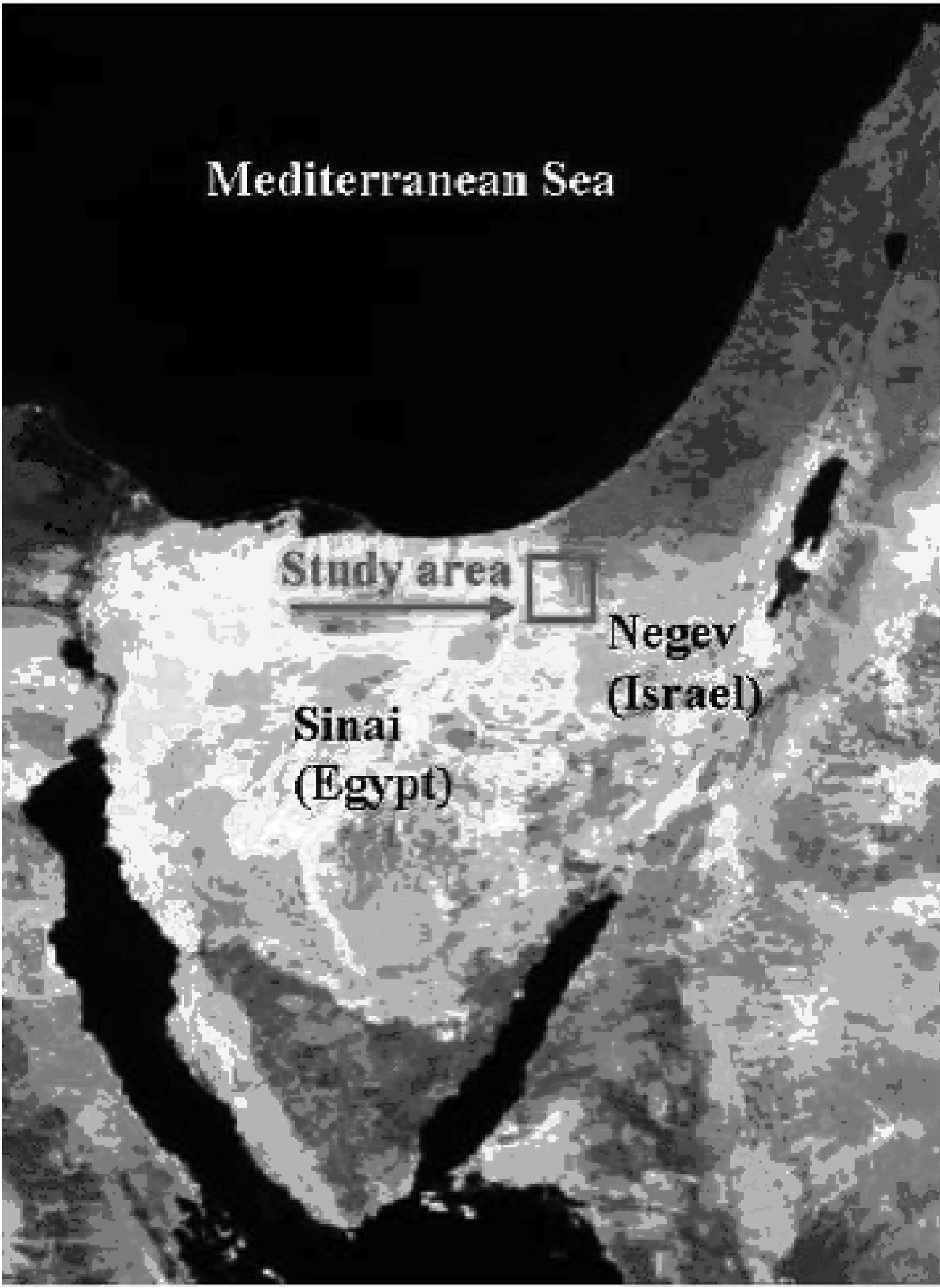

Figure 2. A subset of a NOAA AVHRR image with the study area; acquired in February 1997 during the rainy season (R,G,B = 2,1,1).

4. Analysis and results

4.1. *Spectral ground measurements*

The temporal variation in the spectral reflectance of the main four surface components (sands, perennials, annuals, and biological soil crusts) in the study area during 1 year based on selected months is shown in figure 3. The spectral reflectance of bare surfaces in the Negev almost does not change between the rainy and dry season and shows a high reflectance value in all wavebands with a gradual increase from the visible towards the NIR (figure 3(*a*)). The corresponding biogenic crust spectra during the dry season (figure 3(*b*)) are very similar to that of typical bare soil spectra. They also increase gradually towards the NIR and do not show any photosynthetic activity. However, during the wet season (January) the crust spectrum turns into a typical vegetation spectrum with blue and red absorption dips, relative green peak, red edge, and NIR plateau. The annuals (figure 3(*c*)) present a typical green vegetation spectrum only late in the rainy season (March) and turns into a typical dry vegetation spectrum all year round otherwise. This phenomenon is mainly caused by the change from green annuals in the spring to dead or senescent vegetation in all other seasons. The perennials (figure 3(*d*)) present a spectrum of green vegetation during the rainy season as well as during the dry season. Their typical vegetation spectra is more pronounced in the early summer (June) since the photosynthetic activity decreases during the dry season due to adaptation of the plants to desert conditions (Evenari *et al.* 1982, Danin 1983).

Field observations, based on hand-held spectrometer measurements of different surface components covering two growing seasons (1996/97 and 1997/98), show

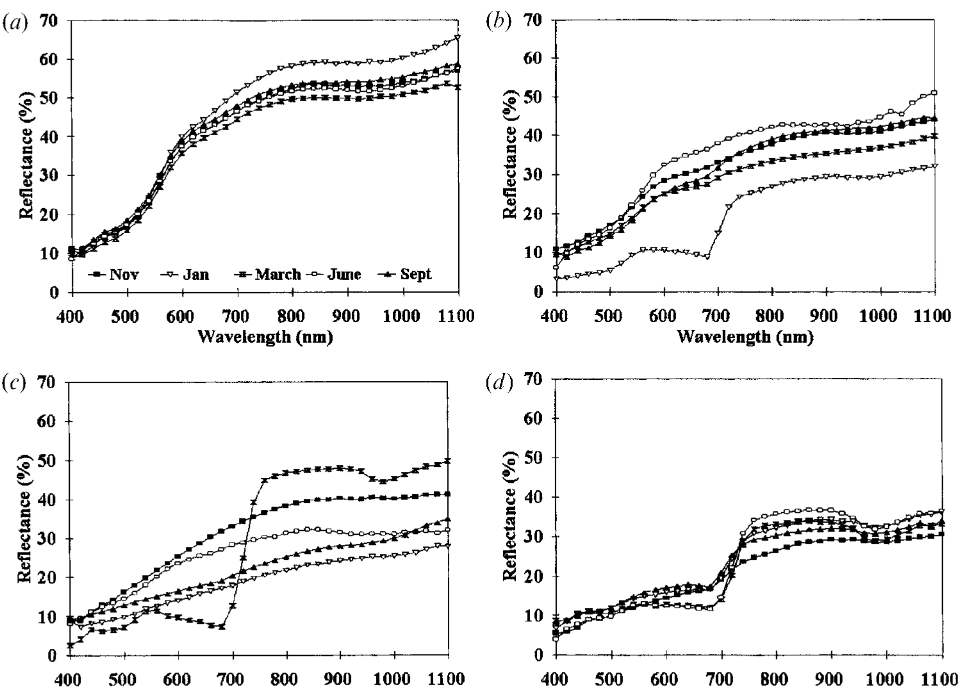

Figure 3. Spectral ground measurements in the Negev study area: (*a*) bare surface (sand), (*b*) biological soil crusts, (*c*) annuals, and (*d*) perennials.

Figure 4. (*a*) Relationship between NDVI (derived from spectral ground measurements) of different surface components and their response to monthly rainfall (mm) in the Negev, and (*b*) weighted NDVI with respect to the percent cover of the surface components.

biological soil crusts, have about a 2-month peak, and decrease to almost zero during the dry season. The perennials are represented by a stable 3-month plateau with slight increase during the rainy season. The peak of the activity of the perennials is at the end of the rainy season (April for both years). From the upper envelope line of figure 4(*b*) one might notice that the annual weighted NDVI values are contributed periodically by the three vegetation components—biological soil crusts at the beginning of the rainy season followed by the annuals, while the perennials at the end of the rainy season and during the dry season.

The relative contribution of each of the different surface components on the overall NDVI signal changes from dry season to rainy season (figure 5). Perennials do not show a significant change in their NDVI contribution for the entire study area. A slight increase can be observed at the end of the rainy season. Annuals change their contribution to the sum of the NDVI signal: from almost zero during the dry season to a high contribution during the first 2 months of the rainy season. The high percentage cover of biological soil crusts is responsible for the high contribution to the overall NDVI signal. However, the contribution of biological soil crusts changes between the seasons and shows a maximum at the beginning of the rainy season. At the end of the rainy season and during the entire dry season, the spectral response of biological soil crusts is almost the same as bare surface and does not show any photosynthetic activity.

Table 2 lists the correlation of determination between the NDVI values of all surface components and: (1) the concurrent month rainfall; (2) the sum of the last 3 months' rainfall (including the concurrent month); and (3) the cumulative rainfall up to a certain month. The highest correlation was found between annuals and the cumulative rainfall of the last 3 months' rainfall ($r^2 = 0.87$). NDVI values of the biological soil crusts show a relative high correlation in cases of the sum of the rainfall of the concurrent month and the two previous months. Perennials and annuals show a much lower correlation with the rainfall of the concurrent month than with the sum of the rainfall of the concurrent month and the two previous months due to the delayed response of their photosynthetic activity.

4.2. *Satellite image processing*

AVHRR data analysis shows a significant spectral difference between both sides of the border in the red channel (figure 6(*a*)) and in the NIR channel (figure 6(*b*)) during the entire studied time period (from June 1995 until June 1998). In both channels Sinai is represented by relatively higher reflectance values than in the Negev. The temporal pattern of the spectral reflectances in the red and NIR channels is almost similar on both sides of the border. During the rainy season the difference

Table 2. Correlation of determination (r^2) between the NDVI values based on spectral ground measurements and rainfall during various time periods.

	Monthly rainfall	Sum of rainfall of the concurrent month and the two previous months	Cumulative rainfall
Perennials	0.01	0.31	0.45
Annuals	0.22	0.87	0.64
Biogenic crusts	0.50	0.55	0.25
Sand	0.04	0.01	0.01

in reflectance between the Israeli and the Egyptian sides of the border is higher than in the dry period, in both channels, as indicated by the ratio of the reflectance values ($\rho_{i\,\mathrm{Sinai}}/\rho_{i\,\mathrm{Negev}}$).

Figure 7 shows the temporal variation of AVHRR/NDVI of almost 3 years of the satellite observations for both sides of the border. The most significant ratio ($\mathrm{NDVI}_{\mathrm{Negev}}/\mathrm{NDVI}_{\mathrm{Sinai}}$) occurs during the growing season, where the Sinai's NDVI are much lower than the respective Negev's values. This shows the relative higher abundance of vegetation in the Negev than in Sinai. A comparison of AVHRR/NDVI with monthly rainfall data from the Negev desert is shown in figure 8. The NDVI pattern is almost similar on both sides of the border. The highest NDVI values are found a few weeks after the main rainfall month(s).

The relative low NDVI values during the 1995/96 rainy season (figure 8) is due to relatively low amount of rainfall at that season (32.3 mm), while the two following successive yearly NDVI peaks reflect average rainfall conditions (79.3 and 85.1 mm, respectively). In comparison to 1995/96, the following two rainy seasons (1996/97 and 1997/98) of average annual rainfall allows a clear distinction between the dry and rainy seasons, especially in the Negev. The rainy season 1996/97 shows a short peak, because most of the rainfall was concentrated during only a few days. Beside, the peak of the NDVI in 1996/97 was earlier than in the following year. The rainfall during the 1997/98 season was more evenly distributed over almost a 2-month period.

In 1995/96 the NDVI peak in November reflects probably the fast response of the biological soil crusts. While the remaining season was with almost no significant

the entire year can be separated into three seasons: I—pre-rainy season (October–January), II—rainy season (February–April), and III—dry season (May–September). The highest Δ_{NDVI} ($NDVI_{max} - NDVI_{min}$) for each month was found during the rainy season for the Negev, while in Sinai this trend does not exist. The magnitude of Δ_{NDVI} is more than twice higher for the Negev than for Sinai. This phenomenon indicates that the Negev has a much higher sensitivity of NDVI to rainfall. This is very important from the ecological point of view. A typical seasonal trend was found only in the Negev. The prolonged dry season is very stable and no major difference between the observed years were found. The pre-rainy season is distinguished from the dry season by a higher Δ_{NDVI}.

A similar temporal pattern between NDVI, observed by the AVHRR sensor and the weighted values NDVI based on the spectral ground of all components (equation 2) is presented in figure 10. The sum of the fractions of all surface components (Σ_{NDVI}) shows a good agreement with the AVHRR/NDVI data for the Negev desert ($r^2 = 0.83$, figure 10). As seen in figure 10, the most pronounced difference between the ground estimated NDVI and the AVHRR/NDVI in the sandy environment was found during the rainy season, when there is an overlay effect of the vegetation components. This is probably due to the fact that the vegetation components in the sandy environment are not spatially well separated. The reason is that biological soil crusts are overlaid by the annuals during the rainy season. At the end of the rainy season, the spectral response of the perennials that overlay partially the biological soil crusts and annuals contribute the main signal as measured by the satellite.

5. Conclusion

The results of the spectral ground measurements on the Israeli side of the border show that all three vegetation components respond differently to rainfall. Annuals show the highest NDVI values, when the fraction or cover of each surface component was not considered. After weighting the fraction of the cover for each vegetation and soil component, the magnitude of the NDVI values changed significantly for each surface component. The contribution of all different surface components on the overall NDVI signal changes from dry season to rainy season. Perennials do not show a significant change in their NDVI contribution for the entire study area. A slight increase can be observed at the end of the rainy season. Annuals change their contribution for the sum of the NDVI signal from almost zero during the dry season to a high contribution during the first 2 months of the rainy season. The contribution of the biological soil crusts changes between the seasons and shows a maximum at the beginning of the rainy season.

AVHRR data analysis shows a significant spectral contrast between both sides during the entire year. The most significant magnitude of the difference between both sides was found during the growing season. The highest correlation was found between AVHRR/NDVI and the rainfall of the concurrent and the two previous months that underlines the delayed response of the higher vegetation in the study

Figure 10. (*a*) Temporal pattern of NDVI observed by AVHRR sensor and the NDVI based on the spectral ground measurements for selected surface types in the Negev. (*b*) Relationship between NDVI observed by AVHRR sensor and the weighted sum of all ground measured surface components.

area. A typical seasonal trend of AVHRR/NDVI values was found in the Negev that indicates that the Negev has a much higher sensitivity to rainfall than Sinai.

The high correlation between the spectral response of perennials/annuals and AVHRR/NDVI data in the Negev desert is due to the fact that the magnitude of AVHRR/NDVI is at the same time as the maximum response of perennials and annuals. The peak of the biological soil crusts is earlier and is followed by the peak of the annuals. AVHRR/NDVI data show only an increase in values, but do not reach a peak in this stage.

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