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Remote sensing of the seasonal variability of vegetation in a semi-arid environment

Heike Schmidt & Arnon Karnieli*

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

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This case study assesses the use of satellite data to monitor the vegetation cover in two types of semi-arid environments — sand dune and rocky — located in the Negev Desert of Israel. In this study, satellite images acquired by NOAA/AVHRR over a time period of 2 years were analysed. The phenological spectral characteristics of vegetation in the two environments are very similar. Comparison between the AVHRR-derived NDVI (Normalized Difference Vegetation Index) values and rainfall data shows dependence of the NDVI values on the sum of the amount of rainfall during the concurrent month and the two previous months. Field observations show that the vegetation components in the two semi-arid environments respond to rainfall with a time lag. The satellite-observed peak of NDVI occurs at the same time as the peak of the delayed response of annuals and perennials to rainfall.

Keywords: satellite data analysis; semi-arid vegetation; NDVI; Negev Desert; phenology; biogenic crusts

Introduction

The study and monitoring of vegetation is an important part of the analysis and interpretation of remote sensing data (Colwell, 1974; Rouse *et al.*, 1974). This information is crucial for understanding processes such as global carbon cycling, terrestrial primary productivity, hydrologic cycles, and terrestrial energy balance (Tucker *et al.*, 1985).

Remote sensing methods have been applied over a number of regions worldwide to monitor vegetation changes (e.g. Tucker *et al.*, 1983; Tucker *et al.*, 1985; Justice & Hiernaux, 1986; Townshend & Justice, 1986; Tucker, 1986; Maselli *et al.*, 1993; Bastin *et al.*, 1995; Hobbs, 1995; Prince *et al.*, 1995). A large number of these works show that remote sensing has been considered to be a useful method for studying arid and semi-arid ecosystems. For example, Peters & Eve (1995) and Peters *et al.* (1997) analysed desert plant community growth patterns and their response to changes of ecological parameters with high temporal resolution satellite spectra. The results of these studies permit the accurate identification of vegetation types of sparse vegetation cover in southern New Mexico. Multi-temporal satellite data have also been used by many

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

researchers to monitor plant phenology (e.g. Justice & Hiernaux, 1986; Townshend & Justice, 1986; Justice *et al.*, 1991; Lambin & Strahler, 1994; Prince *et al.*, 1995).

The multi-spectral and multi-temporal nature of satellite imagery facilitates the investigation of their vegetation component, based on their typical spectral reflectance, mostly in the red (600–700 nm) and near-infrared (NIR) (700–1100 nm) bands of the electromagnetic spectrum (Tucker, 1979; Sellers, 1985). Several sources of satellite data provide the opportunity for the objective analysis of ecological variables such as biomass productivity and vegetation cover. Among them, the Advanced Very High Resolution Radiometer (AVHRR) on board the National Oceanic Atmospheric Administration (NOAA) satellites, with a high temporal frequency of about one image a day for any given location, plays a significant role (e.g. Gutman, 1989; Rasmussen, 1997). The relationship between the AVHRR red and NIR spectral bands and ecological variables (such as biomass and vegetation cover) have been discussed in many publications (e.g. Holben, 1986; Chilar *et al.*, 1991; Ehrlich *et al.*, 1994; Gutman & Ignatov, 1995; Prince *et al.*, 1995).

The most important AVHRR-derived product for ecological applications is the Normalized Difference Vegetation Index (NDVI) developed by Rouse *et al.* (1974):

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

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). Previous workers showed that multi-temporal NDVI images are useful for analysing spatial vegetation pattern and for assessing vegetation dynamics (e.g. Justice *et al.*, 1985; Townshend & Justice, 1986). Using NDVI images derived from AVHRR data, vegetation-cover classes can be separated in a multi-temporal space according to their phenological variations (Justice *et al.*, 1985; Justice & Hiernaux, 1986). Time-series analyses of satellite data enable the observation of seasonal and annual trends in vegetation cover. Assuming that the soils and land use characteristics do not change significantly, comparison of inter-annual and year-to-year NDVI profiles can provide information about the current vegetation condition.

NDVI values derived from AVHRR observations in a semi-arid environment have been found to correlate closely with rainfall (Hielkema *et al.*, 1986; Townshend & Justice, 1986; Gutman, 1991; 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 also a sensitive indicator for the inter-annual variability of rainfall. The timing of NDVI response to rainfall was studied by Nicholson *et al.* (1990). The results of that study showed that there is a good relationship between rainfall variations and NDVI on seasonal and inter-annual time scales.

This study deals mainly with the consideration of problems in remote sensing monitoring of a semi-arid environment. In a desert environment, plants are exposed to extreme conditions and must survive drought, which can stretch over several years with little or no rain. A detailed discussion of the adaptation of perennials to desert conditions can be found in Evenari *et al.* (1982) and Danin (1983). Annuals, in contrast to perennials, germinate only after rain with a substantial amount of water. Their growth and life cycle is limited to the short rainy seasons. During the characteristically prolonged dry seasons, annuals are completely dead and become dry litter on the ground surface.

In the absence of a dense distribution of higher plants, a large part of the arid and semi-arid surfaces are covered by microphytic communities of small non-vascular plants

(West, 1990). These microphytic communities, consisting of mosses, lichens, algae, fungi, cyanobacteria and bacteria, form biogenic crusts over soils and rocks (e.g. Rogers, 1977; Evenari *et al.*, 1982; West, 1990; Johansen, 1993; Eldridge & Greene, 1994; Metting, 1995).

One of the most distinct features of semi-arid environments that affect plant growth is the seasonal and year-to-year fluctuation in rainfall. In arid ecosystems with a single rainy season, there is usually a short growth period followed by a prolonged dry spell with considerable reduction in the amount of green plant material. The phenological change of vegetation has an influence on their seasonal reflectance dynamics. In this work, we have not differented between different species of desert plants. However, three categories of vegetation were studied: perennials, annuals, and lower plant communities.

The objective of this paper is to discuss the application of remote sensing to the monitoring of temporal and spatial variations of the sparse vegetation in two areas located in the Negev Desert in Israel. The two areas are different in terms of geology and pedology, as well as vegetation cover and composition. The research is based on the analysis of NOAA/AVHRR imagery and field measurements acquired during a 2-year period.

Study areas

The study areas are located in the Negev Desert of Israel (Fig. 1). The average annual precipitation for both sites is about 100 mm, and this is concentrated during the rainy season (from November until March). The amount, intensity, and distribution of rainfall varies considerably from year to year. Table 1 lists the annual rainfall measured in Sede Hallamish and Sede Boker over a 3-year time period. The 1995/96 rainy season was very dry and had a total rainfall of 32·3 mm in Sede Hallamish, and 51·3 mm in Sede Boker. The two subsequent rainy seasons (1996/97 and 1997/98) had around average annual rainfall. In the 1996/97 rainy reason, the rainfall distribution was uneven, concentrating mainly within one month (January). The 1997/98 rainy season had two major rainfall events (January and February) with the first one occurring 2 weeks earlier than in the previous year.

The Sede Boker study area is located in the northern Negev Highlands and is characterized by sedimentary rocky terrain composed of Eocene and, to a lesser degree, of Cenomanian, Turonian and Senonian limestone, chalk and dolomite (Evenari *et al.*, 1982). The higher vegetation in this area is mainly represented by *Artemisia herba-alba, Anabasis articulata, Reaumuria negevensis*, and by annuals (Danin, 1983). Most of the limestone and flintstone rocks are covered by different species of lichens (Karnieli *et al.*, 1996). In this test site, field sampling was conducted mainly on hillslopes and lower colluvial sections with denser vegetation cover.

The second study area (Sede Hallamish) is located in the north-western Negev Desert and is a sandy environment (Eocene) which represents the eastern extension of the Sinai sand fields from the geomorphological and lithological points of view (Tsoar & Moller, 1986; Tsoar, 1990; Tsoar *et al.*, 1995). The area consists of longitudinal dunes with wide interdune corridors. The site is characterized by sparse higher vegetation (e.g. *Anabasetum articulatae, Artemisia monosperma, Thymelia hirsuta, Retama raetam,* and *Stipagrostis scoparia*), which is mainly located in the interdunes (Danin, 1983, 1991). The slopes of the dunes and the interdunes are covered by a biogenic crust of mainly cyanobacteria (Karnieli & Tsoar, 1995; Karnieli, 1997). The cyanobacteria communities consist of *Microcoleus vaginatus* accompanied by *Scytonema, Schizothrix, Calothrix, Chroococcidiopsis, Nostoc*, and *Phormidium* (Danin *et al.*, 1989). Karnieli *et al.* (in press) found that the biogenic crusts in this study area differ in their species composition (content of cyanobacteria and mosses), as well as in their microbiological characteristics (chlorophyll content, organic matter, as well as crust thickness). The biogenic crusts that

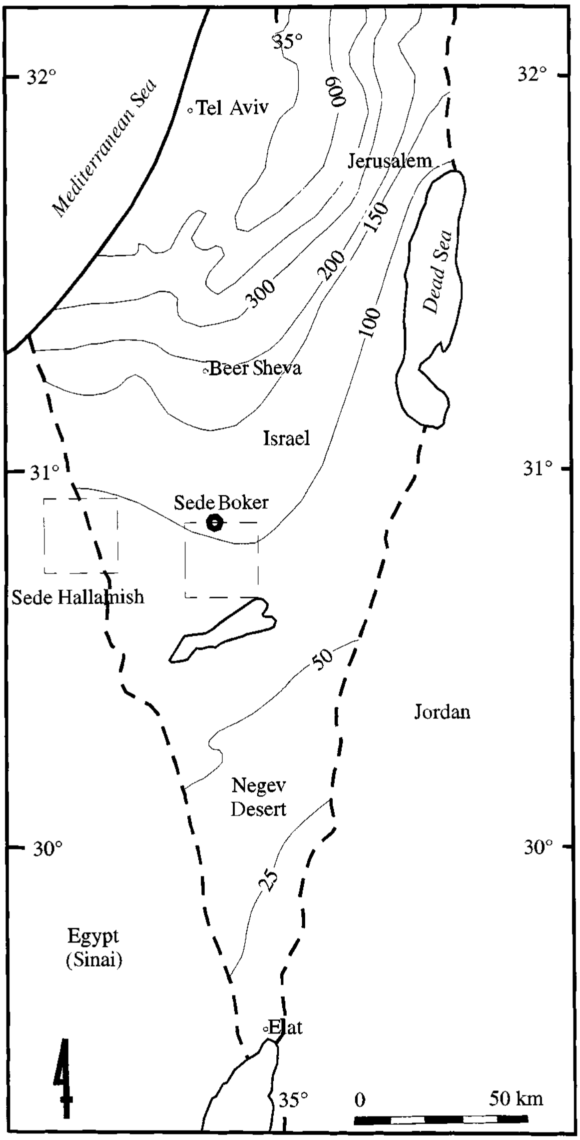


Figure 1. Location of the study areas and the rainfall distribution over the southern part of Israel.

cover the north-facing slopes of the dunes with a total area of about 10% of the study site contain more mosses and organic matter than the biogenic crusts in the interdunes and south-facing slopes (80% of the studied area). These mosses are responsible for a higher spectral signal on the north-facing slopes than in the interdunes and on the south-facing slopes of the dunes.

Table 2 lists the percentages of vegetation cover, differentiated by components, for both study areas during the dry and rainy seasons. The vegetation cover changes observed between the dry and wet seasons are mainly due to the annuals. The spatial coverage of the perennials does not change from one season to another, but their photosynthetic activity changes after the rainfall due to their natural mechanisms for adaptation to desert conditions. A small amount of water is enough for the photosynthetic activity of biogenic crusts.

Table 1. *Annual rainfall (mm) for the Sede Hallamish sand dune area (data from the Arid Ecosystems Research Centre, Jerusalem) and the Sede Boker rocky area (data from the Meterological Unit, Jacob Blaustein Institute for Desert Research, Sede Boker)*

	Sandy environment	Rocky environment
1995/96	32·3	51·4
1996/97	79·3	108·7
1997/98	85·1	96·1

Methods

Spectral ground measurements

In both study areas, 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 biogenic crusts) and various soil and rock types were measured in both study areas.

In order to estimate the overall spectral signal transmitted from different ground components in a digital image, a linear mixture model was used (Ichoku & Karnieli, 1996). The basic physical assumption underlying the linear mixing model is that there is no significant amount of multiple scattering between the different cover types, so that the signal measured by a sensor on a given pixel can be considered 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

Table 2. *Vegetation cover (%) in the sandy and rocky environments based on the 'McAuliffe' method with several 1000 m^2 plots*

	Perennials	Annuals	Microphytes
Sandy environment	(Sede Hallamish)		
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
Rocky environment	(Sede Boker)		
March 1997	7·6	9·5	45
June 1997	7·6	1·2	45
December 1997	7·6	1·2	45
March 1998	7·6	9·3	45

by the following formula:

$$R = \sum_{i=1}^{n} P_i \rho_{ij} \qquad (2)$$

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 both study areas.

The relative percentage contribution of vegetation cover was estimated during the rainy and dry seasons of two years (1997 and 1998) using the McAuliffe method (McAuliffe, 1990). This method allows rapid estimates of density and cover of perennial vegetation in arid environments. Within the study areas, 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. The plots were well distributed in order to represent the area appreciably. The annuals were counted in several 1 m^2 plots within the same study site. The ground data were used as a reference for the satellite data analysis.

Satellite data processing

The present study is based on NOAA/AVHRR satellite data, with a spatial resolution of 1·1 km at nadir, received in Sede Boker almost daily. NOAA-14 AVHRR images of Israel were obtained for the 2-year time period from June 1996 to June 1998. Only cloud-free images were used. The correction procedure was divided into three parts: radiometric correction, atmospheric correction, and geometric correction. The post-launch radiometric calibration of the AVHRR sensor was applied according to Rao's parameters (Rao & Chen, 1996). Atmospheric correction of the top-of-atmosphere (TOA) reflectances was carried out using the 6S algorithm (Vermote *et al.*, 1997). The image data were geometrically corrected to a master image using ground control points. Finally, the NDVI 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 of Holben (1986). This technique reduces directional reflectance and off-nadir viewing effects and minimizes sun-angle and shadow effects.

Results and discussion

Spectral ground measurements

The temporal variation in the spectral reflectance of the four main surface components in the sandy environment (Sede Hallamish) during the rainy (a) and dry (b) seasons is shown in Fig. 2. The spectral reflectance of the sand almost does not change between the rainy and dry seasons, and shows the highest values in all wavebands, with a continuous increase towards the NIR (700–1100 nm). During the rainy season, the annual's spectrum shows the signature of a typical vegetation spectrum, characterized by two absorption features for chlorophyll in the blue (400–500 nm) and in the red (600–700 nm), a relatively high peak in the green (around 550 nm), a sharp slope in the

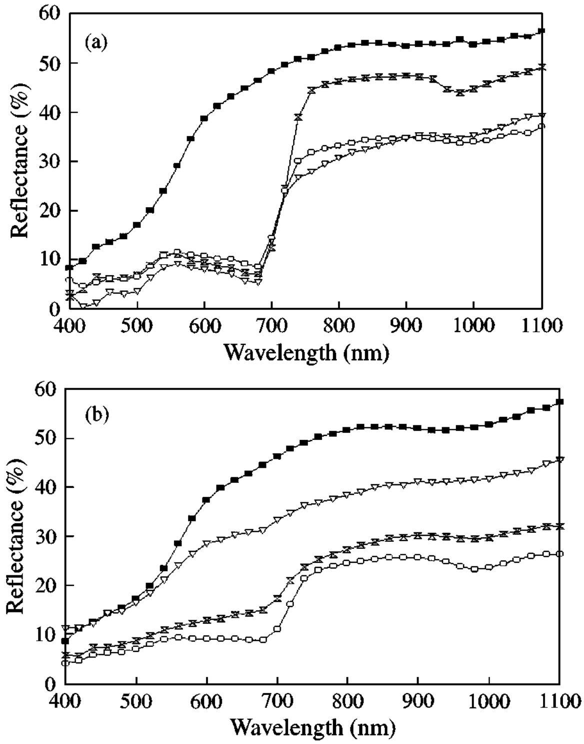
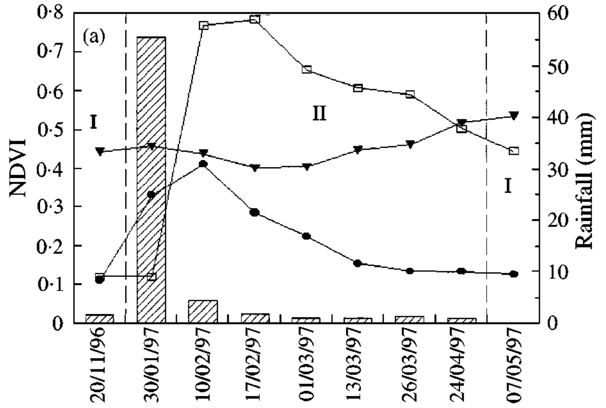


Figure 2. Spectral ground measurements of different surface components in the sandy environment during: (a) the rainy season, and (b) the dry season. ■ Sand; ⧗ annuals; ▽ biogenic crust; □ perennials.

red edge (around 700 nm), and the typical high plateau in the NIR spectral regions. However, during the dry season the vegetation spectrum changes into a relatively low and flat spectrum. This phenomenon is mainly caused by the change from green annuals to dead or senescent vegetation. The perennials are characterized by a spectrum of green vegetation during the rainy season as well as during the dry season, though to a lesser extent. The seasonal decrease in the reflectance level of the NIR plateau from 30 to 20% might be caused mainly by the adaptation mechanisms of the plants to desert conditions. During the rainy season, the biogenic crusts present a typical green vegetation spectrum, which turns into a bare soil spectrum during the dry season with no absorption features caused by photosynthetic activity.

Field observations, based on spectrometer measurements of different vegetation components covering the rainy season 1996/97, show that each vegetation component responds to rainfall differently. Figure 3 describes the relationship between the NDVI based on the spectral ground measurements and the monthly rainfall (mm) in both study areas during the dry (I) and rainy (II) seasons.

Biogenic crusts in the sandy environment respond immediately after the first rainfall (Fig. 3(a)). In the middle of the rainy season, their NDVI values reach a high and sharp peak, which declines rapidly shortly after. Due to the fact that the biogenic crusts on the north-facing slopes and the biogenic crusts in the interdunes as well as the south-facing slopes show a different spectral signature, their spectral response was weighted according to their spatial contribution. The annuals respond later than the biogenic crusts. Their NDVI values have a higher and wider peak that also declines towards the



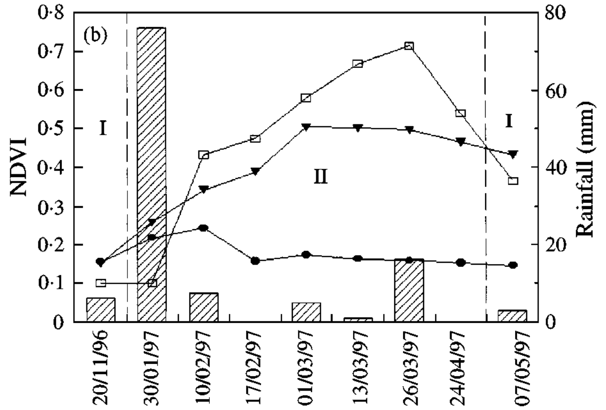


Figure 3. NDVI (derived from spectral ground measurements) of different vegetation components and their response to monthly rainfall (mm) in (a) the sandy environment, and (b) the rocky environment for the 1996/97 rainy season. I, dry season; II, rainy season. ▨ Rainfall (mm); –□– annuals; –●– biogenic crusts; –▼– perennials.

end of the rainy season. During the dry season, biogenic crusts and annuals are represented by low NDVI values, which are almost the same as for bare sand. Perennials in the sandy environment have almost a constant NDVI level throughout the entire time period and respond only towards the end of the rainy season. There is a slight increase of NDVI values from March to May, which declines continuously from the end of May.

The vegetation components in the rocky environment near Sede Boker show a similar phenological trend (Fig. 3(b)). The lichens in the rocky environment show a slight response in the beginning of the rainy season. However, most of the time they are represented by relatively low NDVI values and are less pronounced than the biogenic crusts in the sandy environment. Their NDVI response is also the first to decline. The annuals in the rocky environment respond later than those in the sandy environment and show a very high peak of NDVI values at the end of the rainy season. A sharp decline in response occurs shortly after. The perennial's NDVI increases gradually towards the middle of the rainy season.

The relative contribution of each of the vegetation components to the overall NDVI values has been calculated by multiplying the NDVI value of each component by its percentage cover (Eqn 2). The bare soil and rocks in the rocky environment are 100% covered by lichens (Danin, 1991), while in the sandy environment 90% are covered by

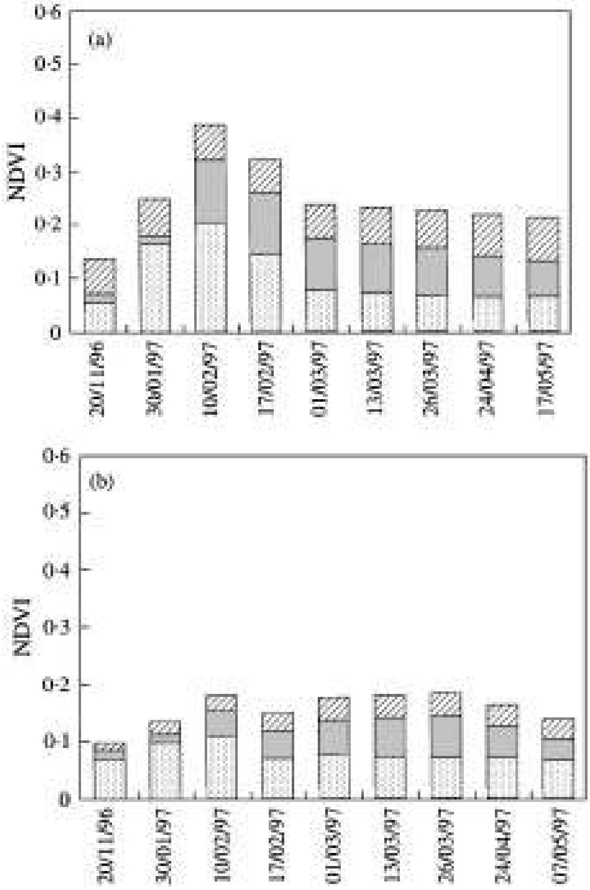


Figure 4. Contributions of the different vegetation components to the overall NDVI signal ($\sum_{NDVI}$), based on spectral ground measurements and estimates of ground cover proportions (in %) in (a) the sandy environment, and (b) the rocky environment. ▤ Biogenic crust; ■ annuals; ▨ perennials.

biogenic crusts and the rest (10%) are covered by bare sands (Karnieli, 1997). The spectral contribution of the sands was included as a weighted part of the biogenic crust component in the sandy environment. Due to the heterogeneity of the biogenic crusts in the sandy environment, the spectral reflectance of the biogenic crusts on the north-facing slopes and in the interdunes were weighted according to their fraction (10 and 80%, respectively). Therefore, the reflectance signal of the biogenic crusts in the sandy environment is based on the weighted sum of the north-facing and the interdune and south-facing communities.

The product of the NDVI values and respective percentage cover for each vegetation component changes from the beginning to the end of the rainy season (Fig. 4). Perennials do not show a significant change in their NDVI for both study areas since their spatial contribution (Table 2) is very low (less than 15%) and almost constant. A slight increase of the spectral signal for the perennials can be observed at the end of the rainy season. Annuals change their contribution to the sum of the NDVI signal: from almost zero at the beginning of the dry season to a higher contribution towards the end of the rainy season. The high percentage cover of biogenic crusts in the sandy environment and the lichens in the rocky environment are responsible for the highest contribution of this component to the overall NDVI signal, especially in the early beginning of the rainy season.

Satellite observations

Figure 5 shows the temporal variation of NDVI during the two years of AVHRR observation for both study areas. The two rainy seasons, (1996/97 and 1997/98), with almost average annual rainfall, are represented by relative high NDVI peaks. Figure 5 also shows the difference between the NDVI values of the two study areas. The most significant difference was found during the growing season. Therefore, it can be inferred that the vegetation causes this difference because background variation plays a minor role between the two areas.

A comparison of AVHRR/NDVI with rainfall data from both study sites is shown in Fig. 6. Both areas show a similar temporal pattern of the NDVI values and rainfall amount with a time lag of about 1 to 2 months. The highest NDVI values were found a few weeks after the main rainfall. The correlation coefficients (r^2) between the AVHRR/NDVI values and the rainfall (mm) for both study areas are listed in Table 3. The correlation was assessed for different month–rainfall combinations: for concurrent monthly values of rainfall; for the rainfall of one and two previous months; and for the sum of the rainfall of the concurrent month and the two previous months prior to the monthly NDVI value of that month. No correlation (r^2 = 0·02–0·05) was found between NDVI values and rainfall amounts of the same time period. In the sandy environment, the highest correlation (r^2 = 0·55) was found between the monthly maximum NDVI values and the rainfall of the concurrent month plus the two previous ones. In the rocky environment, the sum of the rainfall in the two previous months shows the highest correlation (r^2 = 0·55) with the monthly maximum NDVI values. The temporal lags are due to the fact that the vegetation does not respond rapidly to rainfall. Therefore, the highest NDVI values in both study areas were found a few weeks after the main rainy month.

Figure 7 shows the seasonal variation of NDVI acquired by NOAA/AVHRR. Monthly maximum values of NDVI for almost 2 years show a similar seasonal trend for

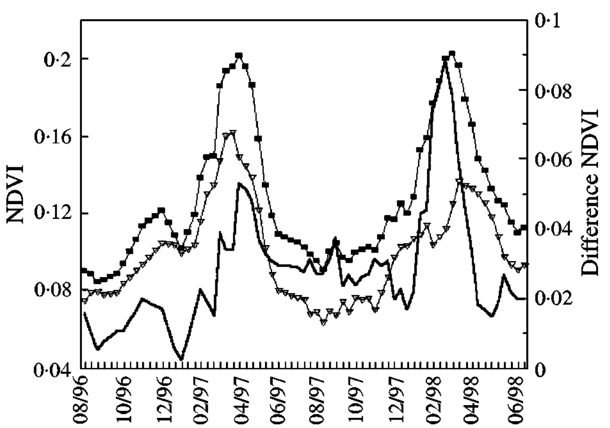


Figure 5. AVHRR/NDVI values (covering a time period of 2 years) for the sandy and rocky environments and the difference in NDVI between the two study areas ($\Delta_{NDVI} = NDVI_{Nizzana} - NDVI_{Sede\ Boker}$). —■— Sandy environment; —▽— rocky environment; —— difference.

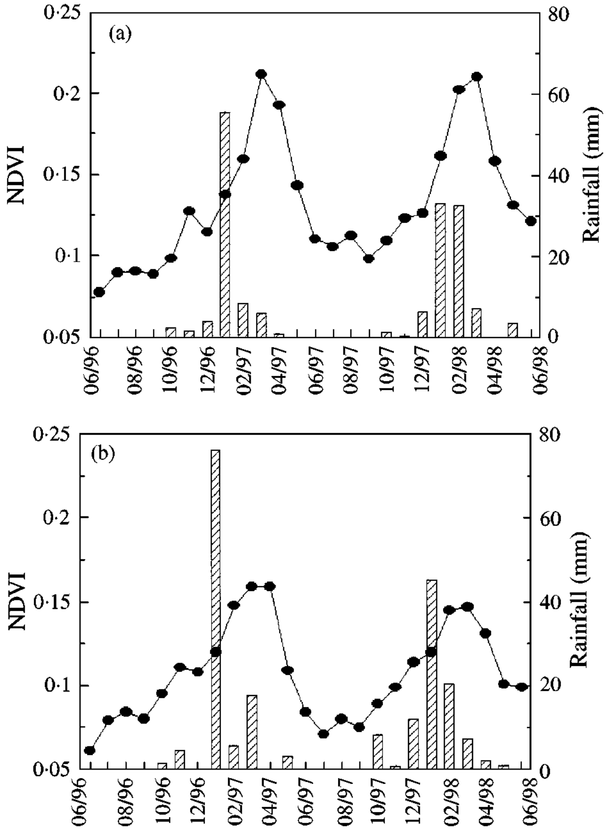


Figure 6. Relationship between monthly maximum AVHRR/NDVI values and monthly rainfall (mm) for (a) the sandy environment, and (b) the rocky environment. ▨ Rainfall; —●— NDVI.

both study areas. For this study, an entire year can be divided into three seasons: I, dry season (May–October); II, pre-rainy season (November–January); and III, rainy season (February–April). In the dry season (the longest period), NDVI values are very low and no major difference was found between the observed years (due to similar rainfall

Table 3. *Correlation coefficients (r^2) between the AVHRR/NDVI and rainfall (mm) data in different rainfall/month combinations in the sandy and rocky environments*

	Sandy environment	Rocky environment
Rainfall in concurrent month	0·05	0·02
Rainfall of the previous month	0·27	0·24
Rainfall of two previous month	0·36	0·25
Sum of the rainfall in two previous months	0·25	0·55
Sum of the rainfall in concurrent and the two previous months	0·55	0·46

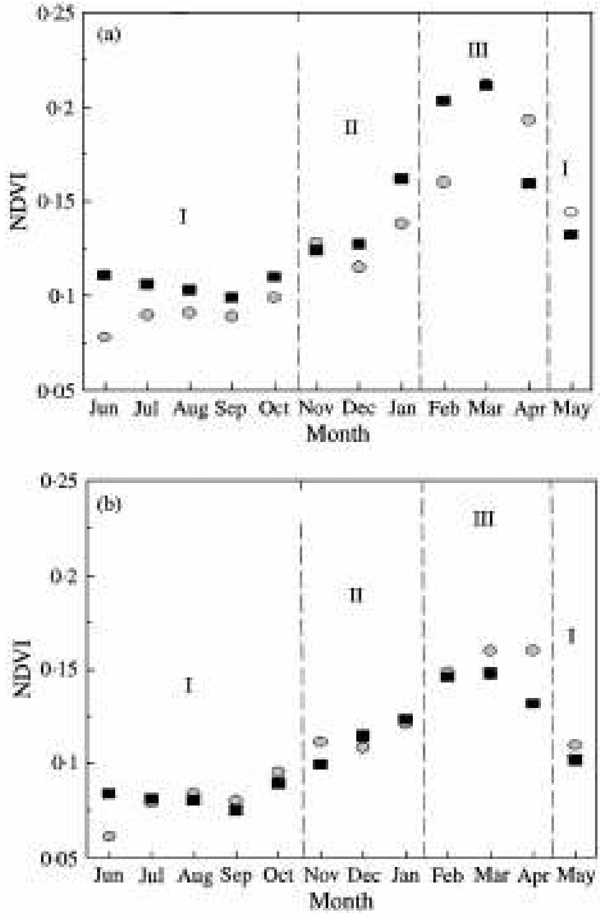


Figure 7. Seasonal and inter-annual variation of monthly maximum AVHRR/NDVI values for (a) the sandy environment, and (b) the rocky environment; acquired from June 1996 until June 1998. I, dry season; II, pre-rainy season; III, rainy season. ○ 1996/97; ■ 1997/98.

distribution in both years). This means that only a few AVHRR-derived NDVI images are necessary to represent this season when monitoring vegetation cover. The following period (November–January) differs from the dry season, showing a slight increase in the NDVI values. The rainy season is characterized by the highest NDVI values. The sandy environment (Fig. 7(a)) shows a higher magnitude of NDVI than the rocky environment. This phenomenon might be due to the more dense coverage of higher vegetation in the sandy environment, particularly of annuals.

The relationship between the NDVI derived from the satellite imagery and the NDVI based on the spectral ground measurements for the selected vegetation components in the two areas is shown in Fig. 8. In order to correlate the two measurements, the spectral ground data were weighted according to the fractional cover of each vegetation component in both study areas by applying the Linear Mixture Model (Eqn 2). A good agreement between the magnitude of the AVHRR/NDVI and the ground-based NDVI was found for the rocky environment with a peak, located 2 months after the main rainfall month.

Table 4 lists the correlation coefficient (r^2) and the estimated standard errors (ε) between the satellite NDVI and ground measured NDVI in the two environments for all

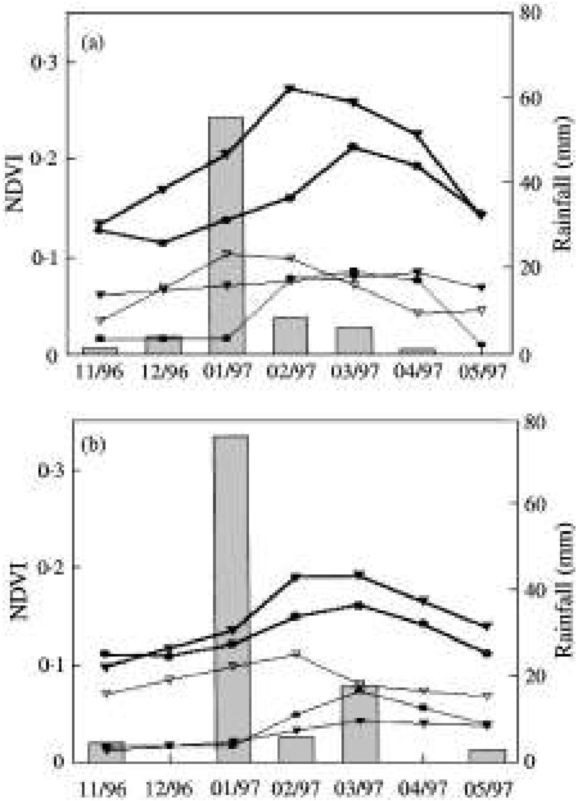


Figure 8. Relationship between NDVI, observed by NOAA/AVHRR, and the NDVI based on the spectral ground measurements for all vegetation components and the weighted sum of all ground measured vegetation components ($\sum_{NDVI}$) in (a) the sandy, and (b) the rocky environments; and their delayed response to rainfall (mm). —▽— Biogenic crusts; —▼— NDVI mixed; —●— annuals; —⬣— AVHRR/NDVI; —▾— perennials.

vegetation components, as well as for the mixed signal of vegetation. In both sites, relative high coefficients ($r^2 = 0{\cdot}74$–$0{\cdot}78$) occurred at about the same time as the peak response of the annuals and perennials. The best correlation ($r^2 = 0{\cdot}84$) was found for the mixed vegetation signal in the rocky environment. This agreement can also be noticed in Fig. 8(b) as similar shapes of the mixed ground NDVI and the AVHRR/NDVI. On the other hand, a lower correlation ($r^2 = 0{\cdot}52$) than in the rocky environment was found for the same relationship in the sandy environment. Figure 8(a) shows that the peak of the NDVI for the ground measurements occurs at the same time as the peak of the annuals and 1 month earlier than the AVHRR/NDVI. The good agreement between the ground based NDVI and the satellite based NDVI in the rocky environment and the less good agreement in the sandy environment can be explained by the different distribution of the vegetation components. In the rocky environment, there is a better spatial separation between the three vegetation components, especially since the lichens cover the exposed rocky surfaces which are not covered by annuals and perennials. On the other hand, in the sandy environment, the biogenic crusts, which are the most effective components in the beginning of the rainy season (Fig. 3), are overlaid later by the annuals. Consequently, the Linear Mixture Model provides better results where the vegetation components can be spatially separated than in areas with multi-layer components.

Table 4. *Correlation coefficients (r^2) between the NDVI based on satellite and ground observations and the estimated standard error (ε) of the linear regression for all vegetation compoenents in both study areas*

	Sandy environment		Rocky environment	
	r^2	ε	r^2	ε
Perennials	0·78	0·004	0·42	0·008
Annuals	0·55	0·033	0·74	0·011
Biogenic crust/lichens	0·03	0·061	0·15	0·017
Mixed signal of vegetation	0·52	0·042	0·84	0·014

The estimated standard errors (ε) between the satellite NDVI and ground measured NDVI was found to be very small for perennials and annuals in both environments. This indicates a relative high standard error was estimated for the biogenic crusts and the mixed vegetation signal in the sandy environment.

Summary

The results of the spectral ground measurements show that temporal analysis of natural vegetation in semi-arid environments should take into account three ground components — annuals, perennials and biogenic crusts/lichens. Each vegetation component has a different phenological cycle, although when integrating the three, the typical phenological response to rainfall is presented. Biogenic crusts and lichens are very sensitive to moisture and turn green during the first rainy month. Their phenological cycle, in terms of weighted NDVI peaks, is the highest and the shortest. The annuals cover the ground only after a few intensive rainfall events. They show a significant response only after a few weeks from the beginning of the rainy season. Their NDVI peak is lower but wider than that of biogenic crusts and lichens. Perennials are photosynthetically active throughout the year, but a show higher spectral response towards the end of the rainy season. The highest correlation between rainfall and vegetation growth is found for annuals, which also show the highest seasonal spectral variability.

The contribution of the different vegetation components to the overall NDVI signal changes from the beginning to the end of the rainy season. Perennials do not show any significant change in their NDVI contribution at any time of the year in both study areas. Annuals change their contribution to the mixed NDVI signal with a peak in the first month of the rainy season. The high percentage cover of biogenic crusts in the sandy environment and the lichens in the rocky environment are responsible for the high contribution of these surface types to the overall NDVI signal.

The most significant difference between the sandy and rocky environments in the AVHRR/NDVI signal was found during the growing season (February to April), which indicates the influence of the vegetation. NDVI values derived from AVHRR time series show that annuals and perennials are the main contributors to the yearly maximum peak, because in both study areas the highest NDVI values were found a few weeks after the main rainfall.

Due to the multi-layered components in the sandy environment, the mixed vegetation signal does not show a strong correlation with AVHRR/NDVI data. The better spatial separation between the three vegetation components results in a higher correlation between the satellite and ground-based observations in the rocky environment than in the sandy environment. However, a typical seasonal trend indicative of higher sensitivity to rainfall was found in the AVHRR/NDVI values for both study areas.

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