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ORIGINAL ARTICLE

Arnon Karnieli

Natural vegetation phenology assessment by ground spectral measurements in two semi-arid environments

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Abstract Natural vegetation in semi-arid regions is characterized by three ground features, in addition to bare surfaces – biological soil crusts, annuals, and perennials. These three elements have distinguishable phenological cycles that can be detected by spectral ground measurements and by calculating the weighted normalized difference vegetation index (NDVI). The latter is the product of the derived NDVI of each ground feature and its respective areal cover. Each phenological cycle has the same basic elements – oscillation from null (or low) to full photosynthetic status and back to a stage of senescence. However, they vary in phase. The biological soil crusts show the earliest and highest weighted NDVI peak during the rainy season, and their weighted NDVI signal lasts longer than that of the annuals. The annuals are dominant in late winter and early spring while the perennials predominate in late spring and during the summer.

Keywords Phenology · Spectral measurements · Semi-arid environment · NDVI · Linear mixture model

Introduction

The term *phenology* is usually defined as "the study of the timing of recurring biological phases, the cause of their timing with regard to biotic and abiotic forces, and the interaction among phases of the same or different species" (Lieth 1974). Phenological cycles can be easily assessed by remote sensing, because this technique has the ability to monitor the biophysical properties of vegetation (such as pigment concentration, leaf structure, etc.) and also to record the ground surface continuously over space and time. Considerable attention has been given to monitoring phenology in agricultural fields and forest. This is usually applied to a single crop or a major biome type (e.g., Reed et al. 1994; Muller 1995; Akiyama et al. 1996; Goetz and Prince 1996). Other phenomena, such as two or three major crops growing simultaneously with different phenological cycles or several crops growing successively in the same field, have also been investigated (e.g., Fischer 1994). However, similar research hardly exists for natural vegetation, especially in arid and semi-arid environments; only one phenological cycle has been considered for an entire year or during the wet season (e.g., Justice et al. 1985; Tucker et al. 1985; Shinoda 1995; Lambin 1996; Rasmussen 1997).

Natural vegetation in semi-arid regions is composed of three ground features – biological soil crusts, annuals, and perennials (Karnieli et al. 2002). Field observations suggest that the traditional seasonal phenology cycle of natural desert vegetation can be broken into three components that are similar to the above three ground features (Fig. 1) and in a way that is not commonly considered, either in agricultural areas or in humid regions.

The microphytic communities of the biological soil crusts are very sensitive to moisture and turn green immediately after the first rain when the soil surface and the upper soil layer are wet. Consequently, large desert areas turn green at the beginning of the wet season, exclusively because of the biological soil crusts, the microphytic community exhibiting peak biomass at this time when the annuals have not yet germinated and the perennials have hardly sprouted. Biological soil crusts have considerable importance in the overall production of the greenness signal in arid environments, where the higher plants are sparse. However, biological soil crusts

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A. Karnieli (✉)
The Remote Sensing Laboratory,
Jacob Blaustein Institute for Desert Research,
Ben Gurion University of the Negev,
Sede Boker Campus 84990 Israel,
e-mail: karnieli@bgumail.bgu.ac.il
Tel.: +972-8-6596855
Fax: +972-8-6596805

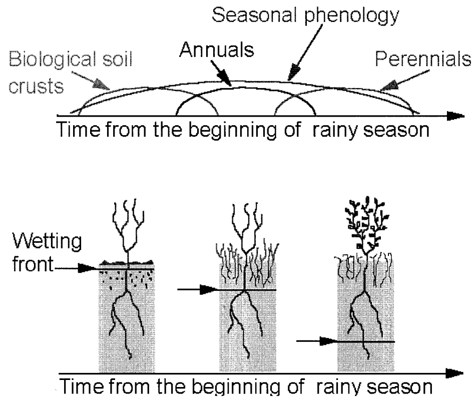

Fig. 1 *Top* The traditional seasonal phenology cycle of the natural desert vegetation can be broken into three components: the biological soil crusts, annuals, and perennials. *Bottom* The temporal dynamics of these cycles depends mainly on the availability of subsurface water

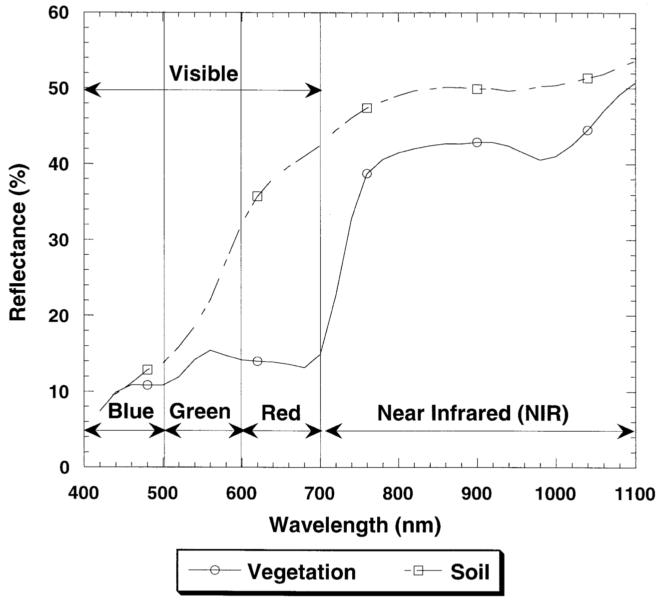

Fig. 2 Schematic illustration of typical spectra of soil (❑) and vegetation (◯)

should be considered as bare soil throughout the dry season (Karnieli et al. 1996, 1999, 2001).

Annual plants germinate after the wetting front reaches a depth of a few tens of centimeters and water becomes available to the concealed seeds. They are green for only a relatively short period during the wet season. The onset of annuals is considered to occur after the first effective rain, defined as 10–20 mm cumulative rains within 15 days (Evenari et al. 1982; Noy-Meir 1973; Danin 1983, 1991, 1996). During the dry period, annuals seem completely dead and the remains of their above-ground parts produce the spectral signal of dry organic matter. According to Evenari et al. (1982), 59% of the Negev winter species are winter annuals. The numbers of annual species and of individuals of each species are extremely dependent on the amount of rainfall, as well as the distribution of the rainy days throughout the wet season.

Perennial desert plants have to adapt themselves to scarcity of water. Adaptation may be morphological, physiological, or behavioral in nature and affects the pigment concentration and/or the leaf structure (Evenari et al. 1982; Danin 1983). For example, desert plants are able to reduce their transpiring surface. Sprouting and full photosynthetic activity of the perennials occur only after water reaches their relatively deep roots. Thus, their phenologicaly cycle starts a few months after that of the biological soil crusts and annuals.

Typical spectra of soil and vegetation are demonstrated in Fig. 2. It can be seen that the reflectance values of the soil spectrum are relatively low in the blue region (400–500 nm) of the electromagnetic spectrum and increase progressively towards the near-infrared region (700–1,100 nm). The vegetation reflectance values are relatively low in the visible part (400–700 nm) especially in the blue and red (600–700 nm) owing to pigment absorption (particularly chlorophyll) and are relatively high in the near-infrared region, because of the cellular structure of the leaves.

From the remote sensing point of view, vegetation indices have been frequently used for monitoring the physiological state and spatial distribution of vegetation, using spectral ground, air, or space data (see Tucker 1979; Asrar et al. 1984; Vogelmann 1990). The most widely used vegetation index is the normalized difference vegetation index (NDVI) (Rouse et al. 1974), which is based on the difference between the maximum absorption of radiation in the blue and red spectral band and the maximum reflection of radiation in the near-infrared spectral band (Fig. 2). Lacking the plants' absorption/reflectance mechanisms, soil spectra typically do not show such a dramatic spectral difference. NDVI is formulated as:

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

where ρ is the reflectance value in the indicated spectral bands. Values of the NDVI range between –1.0 and +1.0 but are usually positive for soil and vegetation. Denser and/or healthier vegetation will have higher values. NDVI values for vegetation usually offer the means of efficient and objective evaluation of phenological characteristics (e.g., Justice et al. 1985; Reed et al. 1994; Running et al. 1995).

Objectives

The objectives of the 3-year study were (1) to prove that the three-phase theory of seasonal phenology of natural vegetation in the Israeli Negev desert is detectable by spectral ground measurements, and (2) to assess the relative spectral, spatial, and temporal contribution of each of the three plant categories – biological soil crusts, annuals, and perennials – to the overall spectral reflectance of semi-arid environments.

Materials and methods

Research sites

The research was conducted in two different ecosystems, loess and sands, in the Northern Negev Desert of Israel (Fig. 3). The first is the Sayeret Shaked Ecological Park near Beer-Sheva in the northern Negev (31°17′N, 34°37′E). This site is denoted hereafter as the loess environment. Rainfall in the study site, limited to the winter months, has a long-term annual average of 200 mm. The landscape is hilly and consists of loessial soils, 1.1 m deep, composed of 59% sand, 27%, silt and 14% clay. The area, which has been closed to livestock grazing since 1987, is covered by scattered patches of shrubs: *Noeae mucronata* (Forssk.) Asch. et Schw. (Chenopodiaceae) and *Atractylis serratuloides* Sieb. (Compositae). The soil surface between the shrubs is completely covered by biological soil crusts, composed of cyanobacteria (mainly *Microcoleus vaginatus, Nostoc punctiforme*, and *Chroococcus* sp.) soil cyanophilous lichen (*Collema* sp.) and two species of moss (*Aloina bifrons*, and *Crossidium crassinerve var. loevipilum*). These microphytic communities are 10–15 mm thick. On the average, the ground cover of the biological soil crust is 50%, 20% annuals, and 30% perennials.

The second site is the Nizzana sand field that is located in the central-western Negev (30°75′N, 34°22′E) and represents the eastern extension of the Sinai continental sandy area. This site is denoted hereafter as the sand environment. It is a fenced-off area with minimal anthropogenic activity over the last 20 years. The average annual rainfall in the area is about 90 mm. The landscape is characterized by linear west–east-trending sand dunes. The upper part of the dunes is composed of unconsolidated sand and is almost devoid of vegetation. The basal dunes and the interdune corridors (about 90% of the area) are stabilized with perennials and a smooth and relatively continuous cover of biological soil crusts. Here, the soil texture is 76% sand, 17% silt, and 7% clay. This area is sparsely vegetated by *Retama raetam* (Forssk.) Webb (Papilionaceae), *Anabasis articulata*, (Forssk.) Moq. (Chenopdiaceae), *Artemisia herba-alba* Asso (Compositae), and *Thymelaea hirsuta* (L.) Endl. (Thymelaeaceae) on the lower slopes, as well as grass, *Stipagrostis* sp. (Gramineae), on the dune crests. The biologenic soil crusts consist mostly of cyanobacteria, where *Microcoleus vaginatus* is the dominant species accompanied by *Scytonema, Schizothrix, Calothrix, Chroococcidiopsis, Nostoc* and *Phormidium*. Mosses are relatively rare. Their dominant species are *Pterygoneurum, Aloina, Bryum bicolor, Brachymenium exile* and *Tortula muralis*. Bare sands comprise 10% of the ground cover, biological soil crusts 70%, annuals 5%, and perennials 15%.

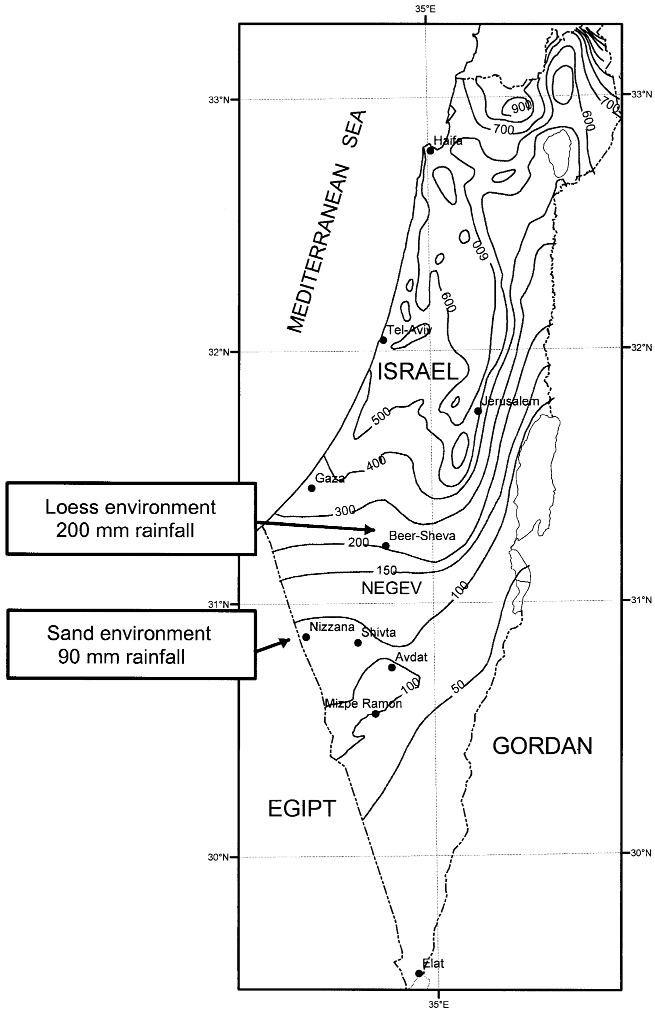

Fig. 3 Location of the study sites in Israel with respect to the rainfall mean annual isohyets

Methodology

Two different, though conceptually close, methods that lead to similar goals, were followed at the two study sites. In the loess environment, three study plots, each 15 × 5 m in size, were marked-out on the north-facing hill slope in the study area. During the 20 months of observation, there were a total of 13 sampling days at intervals of 1 or 2 months. Data for intervening months, in which there was no field sampling, were obtained by linear interpolation from field-measured data. On each of the sampling days, the following operations were performed.

Field measurement was conducted with the Cropscan multispectral radiometer. This radiometer uses eight wavebands centered at intervals of 50 nm between 460 nm and 810 nm. The optical head (MSR87), with a 28° field-of-view, was held level by a support pole about 2.5 m above the ground. The radiometer was designed to measure simultaneously the downwelling irradiance and the upwelling radiance, and its software calculates the percentage reflectance for each waveband. Fifteen successive spectral measurements were taken at fixed points in each of the three experimental plots. Therefore, 45 repetitive measurements were conducted and averaged, giving five mean spectral sets for each sampling day. All were performed on clear days.

The percentage of areal cover of the different ground features was assessed by above-ground photography. A 35-mm still camera was installed on a metal tripod at a height of 4 m above the ground surface. The camera was mounted upside-down. The tripod was moved along the study plots between exposures, such that five single color photographs covered each plot with some overlap. Each five-photograph set was mosaicked to create a single image covering each study plot. Three cross-sections were drawn along the long axis of the mosaic and the percentage of areal cover of each of the three ground features was estimated along these sections.

Leaves (and sometimes also stems) were clipped from each representative species of the higher vegetation in the study area for spectral laboratory measurements. Samples of biological soil crusts were collected in Petri dishes for the same purpose. In the laboratory, the reflectances of the leaf and crust samples were studied using a Li-Cor LI-1800 spectrometer. The instrument was set to a 15° field-of-view, and a spectral resolution of 2 nm wavelength, in a range of 400–1,100 nm.

In the sand environment, reflectance values were measured by a Li-Cor LI-1800 spectrometer with the same configuration as that described above. The spectrometer was hand-held at about 1 m above the different ground features – perennials, annuals, biological soil crusts, and bare sands. The spectral reflectance was calculated by relating the target radiances to the downwelling irradiation as measured by a cosine-corrected receptor. 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 percentage areal cover of the various vegetation components was estimated during the rainy and dry seasons of 2 years (1997 and 1998) following the McAuliffe method (McAuliffe 1990), which allows rapid estimation of density and cover of perennial vegetation in arid environments. Within the test site, certain points were selected as centers of circular plots. The plots had a radius of 18 m (area = 1,018 m^2). All shrubs with different diameters were counted, and the percentage cover was estimated on the basis of a logarithmic formula. The plots were well-distributed along a transect from one dune to another, in order to represent the area adequately. The annuals were counted in 1-m^2 plots along the same transect.

Each spectral analysis involved NDVI calculations according to Eq. 1. In order to assess the relative contribution of each ground feature to the overall vegetation signal of a study area under investigation, for a particular month, a linear mixture model was applied, formulated as:

$$\mathrm{NDVI}_{\mathrm{W}i} = \sum_{j=1}^{n} (f_j M_{ij}) \qquad (2)$$

where $\mathrm{NDVI}_{\mathrm{W}i}$ is the weighted NDVI in the i-th month, f_j is the percentage of area covered by j-th cover type, M_{ij} is NDVI of the j-th cover type in the i-th month and n is the number of cover types, also termed end-members, i.e., three in the loess area and four in the sand study site.

Analysis and results

Figure 4 represents the temporal distribution of the monthly rainfall during the 3 years of research in the two study sites. The Beer Sheva meteorological station data show the rainfall for the loess environment while those of the Nizzana meteorological station show the rainfall for the sand environment. It may be seen that, during the first year of research (hydrological year 1994, 1995), the cumulative rainfall in the loess environment was higher than the long-term annual mean. However, most of the rainfall was concentrated at the beginning of the season and the annual mean was reached in December. January was totally dry with no rainfall, and later that year there was a small amount of rainfall in February, March, and April. The second year was a drought year, and the cumulative rainfall reached only about half the annual mean. Each month from December to March received about the same amount of rainfall. The third year of

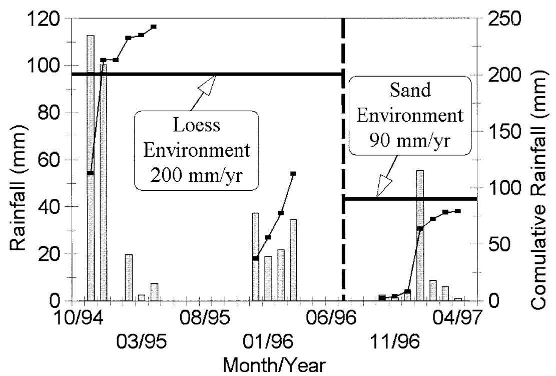

Fig. 4 Monthly rain distribution and cumulative rainfall in the two study sites for the 3 years of research

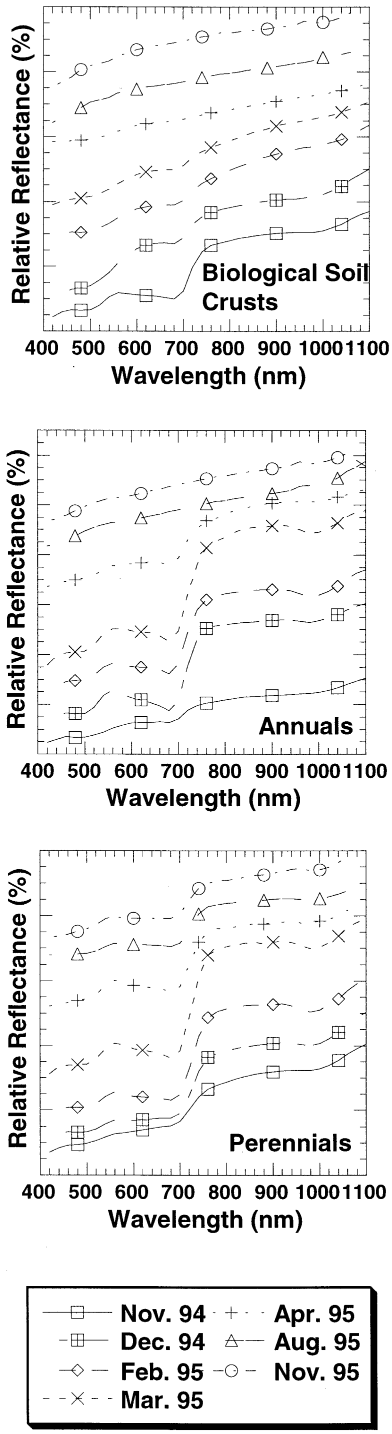

Fig. 5 Spectral reflectance dynamics of biological soil crusts, annuals, and perennials during 2 hydrological years in the loess environment. Curves have been vertically shifted for clarity

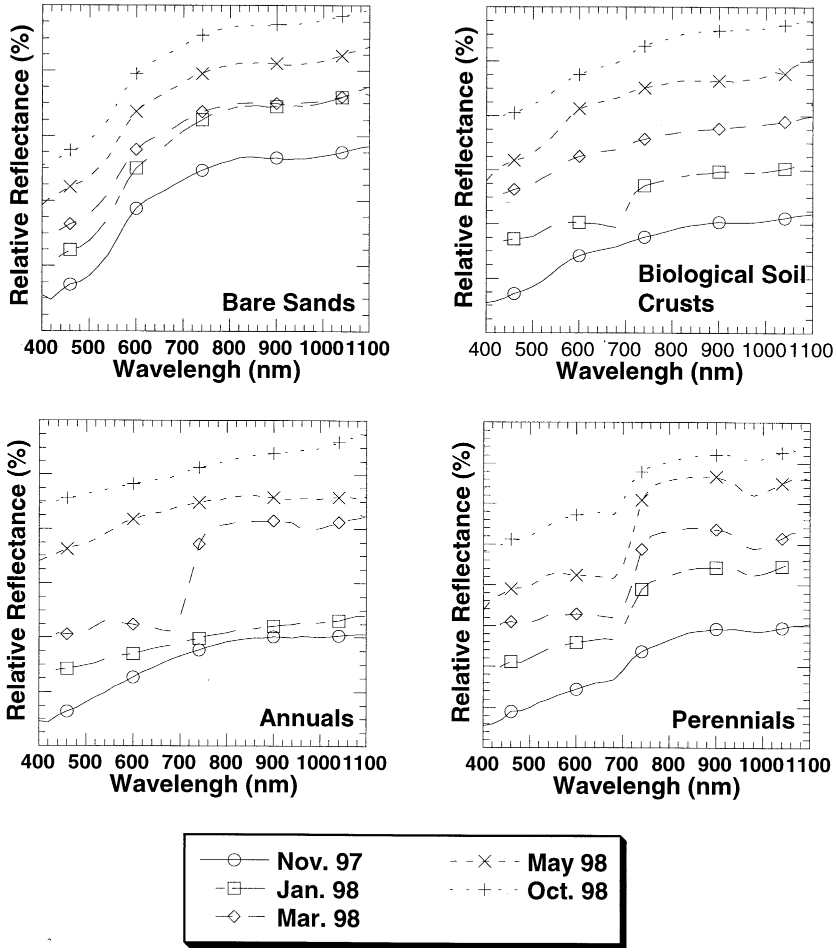

Fig. 6 Spectral reflectance dynamics of bare sands, biological soil crusts, annuals, and perennials during 1 hydrological year in the sand environment. Curves have been vertically shifted for clarity

research was characterized by a symmetrical normal distribution of rainfall, with a peak in January. The cumulative amount was close to the long-term annual mean.

Figure 5 demonstrates the temporal spectral dynamics of the ground features in the loess environment during several selected months in 1 hydrological year. The curves have been vertically shifted for clarity. The biological soil crusts have a spectrum similar to that of high vegetation as early as November, evidenced by their photosynthetic activity, owing to the heavy rainfall in that month. There is a slight dip in the red wavelengths in the following winter months. This dip disappears gradually until March and later becomes similar to that of a soil. The spectrum of the annuals does not exhibit any vegetation signal in November, but does so in December. The annuals remain green until March. Their greenness signal is weak in April and disappears during the summer months. Perennials have a vegetation shape of the spectrum all year round, but its intensity changes. In the hydrological year under discussion, which was characterized by very heavy rainfall at the beginning of the rainy season, the peak greenness of the perennials occured in March. Note that there is no bare soil in the loess environment because of a 100% cover of biological soil crusts.

A similar representation for the sand environment is shown in Fig. 6. The shape of the reflectance curves of bare sands does not change during the year. The typical soil spectrum increases gradually from the visible towards the NIR. The corresponding spectra of the biological soil crusts during the dry months are very similar to that of typical bare soil spectra. They also increase progressively towards the near-infrared and do not show any photosynthetic activity. Only during the wettest month (January) does the biological soil crust spectrum become a typical vegetation spectrum, with blue and red absorption dips, a relative green peak, a red edge, and a near-infrared plateau. The annuals present a typical green vegetation spectrum late in the rainy season (March), otherwise they show a typical dry vegetation spectrum all year around. This phenomenon is caused mainly because the green annuals of the spring turn into dry organic matter during the other seasons. The perennials present a spectrum of green vegetation during the rainy season as well as during the dry season. Their typical vegetation spectrum is more pronounced in the late spring (May), since the photosynthetic activity decreases during the dry season because of adaptation of the plants to desert conditions.

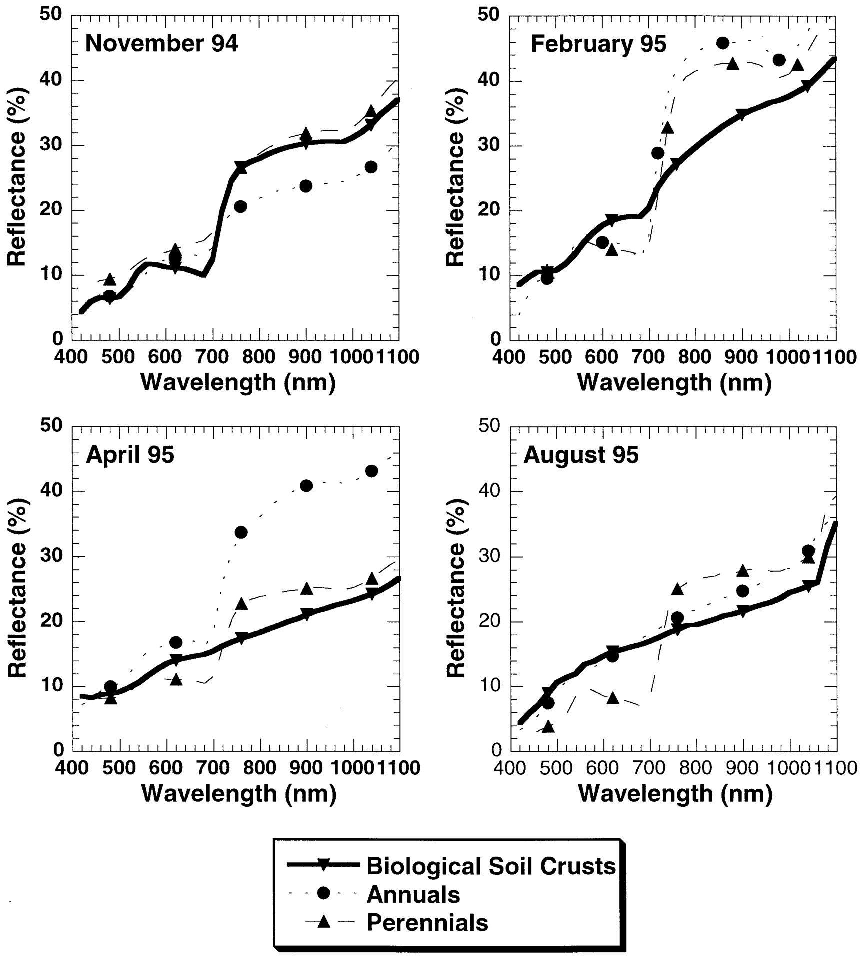

Fig. 7 Spectra of biological soil crusts (▼), annuals (●), and perennials (▲) in selected months, in the loess environment

The relative appearance of the different ground features in several selected months during the hydrological year is demonstrated in Figs. 7 and 8 for the loess and sand environments respectively. In November, for the loess environment (Fig. 7), only the biological soil crusts have a typical vegetation spectrum (see also Fig. 2). In February, when the spectrum of the biological soil crusts becomes a typical soil spectrum (see also Fig. 2), the annuals and perennials exhibit full photosynthetic activity. A similar situation exits in April, but in August, only the perennials show activity. In November, for the sand environment (Fig. 8), all four ground features exhibit the same typical soil spectrum before the rains of the year begin. In January, the wettest month of that year, the biological soil crusts have the most pronounced greenness signal. March is characterized by a typical vegetation spectrum of annuals and perennials; however, this soon changes. In May, only the perennials provide a typical vegetation spectrum, and all the other ground features show a typical soil spectrum.

Figure 9 presents the 2-year weighted NDVI dynamics of the three ground features in the loess environment as calculated by the linear-mixture model of Eq. 2. As shown by either the upper envelope line of the three ground features or the linear-mixture line, three successive phases of the ground features appear one after the other in each year. The envelope line better illustrates the different phenological cycles, while the linear-mixture line shows the overall greenness signal of the site. The first phase is that of the biological soil crusts, the second is that of the annuals, and last, the perennials.

Although the spectral signal of the biological soils crusts is relatively weak, it should be noted that their weighted NDVI peak is the highest owing to the large cover of this ground feature in the study site (more than 70%). The domination of the biological soil crusts can last 2–3 months, and is replaced by the domination of the annuals, which also lasts 2–3 months, although with a somewhat lower peak. The NDVI signal of the perennials governing the rest of the months, decreases gradually from late spring to early fall depending on the rainfall distribution. The highest NDVI value during the first year (when rainfall greatly exceeded the annual mean) was about 0.5 unit. During the second year (when the yearly rainfall was much less than the annual mean) the NDVI value was about 0.35 unit. A similar pattern appeared in the sand environment (Fig. 10) where the peak NDVI value was as high as 0.28 unit. In the 1996–1997 hydrological year, the domination of the soil biological crusts lasted 3–4 months, and that of the annuals 1–2

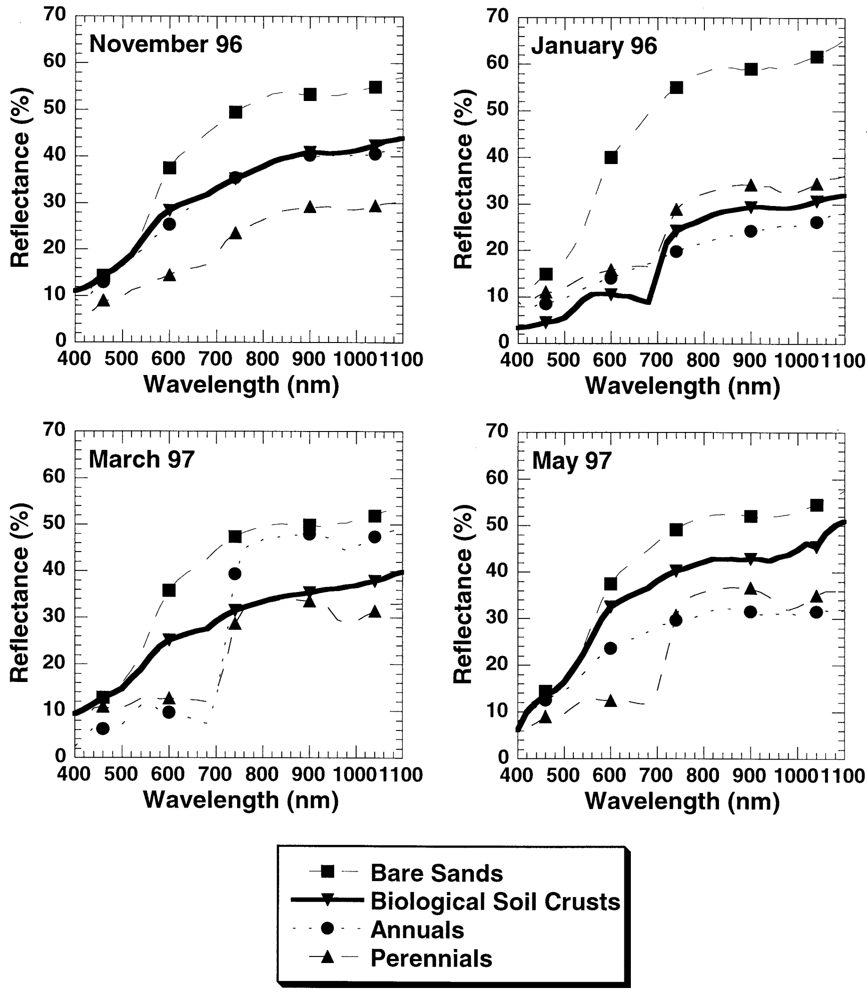

Fig. 8 Spectra of bare sands (■), biological soil crusts (▼), annuals (●), and perennials (▲) in selected months, in the sand environment

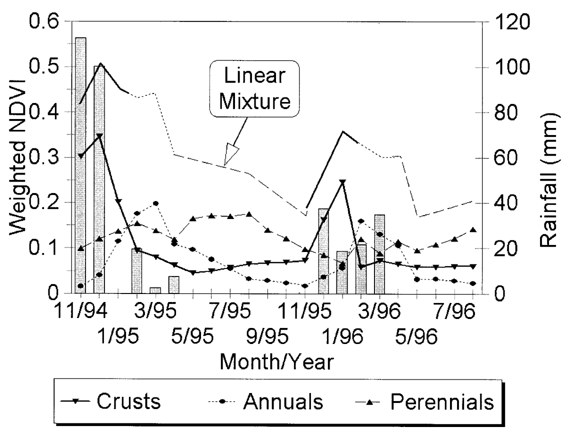

Fig. 9 Temporal dynamics of weighted the normalized differences vegetation indexes (*NDVI*) of biological soil crusts (▼), annuals (●), and perennials (▲) along with results of a linear-mixture model of these ground features during 2 hydrological years in the loess environment

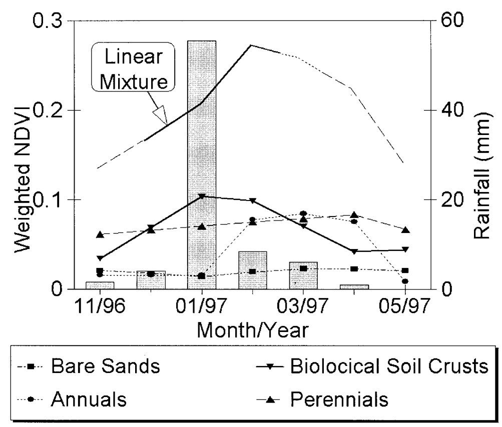

Fig. 10 Temporal dynamics of weighted NDVI of bare sands (■), biological soil crusts (▼), annuals (●), and perennials (▲) along with results of a linear mixture model of these ground features during 1 hydrological year in the sand environment

months. Note that, as expected, the NDVI values of the base sands are low and almost constant for the whole year.

Discussion

Although phenology often describes the rate and timing of a growth cycle of a single crop or vegetation type, this paper shows that it is possible to distinguish between several types of vegetation or land-cover categories by combining information on their spectral, spatial, and temporal distributions. In the current study, three vegetation types were characterized – biological soil crusts, annuals, and perennials. If bare soil exists, it also should be taken into consideration. The spectral signatures of each of the ground features were extracted by means of spectral measurements on the ground and in the laboratory. The corresponding percentage areal cover was also assessed. The NDVI values of each ground feature were derived and, in conjunction with the percentage areal cover information for each sampling date, the weighted-NDVI values were calculated.

Although two different ecosystems were involved in the current study, which lasted 3 years under different precipitation amounts and patterns of rainfall distribution, the same conceptual model holds as hypothesized and presented in Fig. 1. The combined ground spectral measurements of these three ground features demonstrate three phenological cycles with the same basic elements: oscillation from null (or low) to full photosynthetic status and then back to the senescence stage resulting into cycles that do not overlap.

The biological soil crusts have the fastest response to rainfall. They immediately turn green and begin their photosynthetic activity. From the remote sensing point of view, they reflect very similarly to the higher vegetation. Therefore, the spectral signal of the biological soil crusts is especially important at the beginning of the rainy season when the annuals have not yet germinated and the perennials are still dry. Next, the annuals cover the ground. Different annuals can germinate at different times throughout the wet season and therefore more than one peak of greenness might be seen. Only when the annuals dry out do the perennials become the dominant plants. Although perennials use their adaptation mechanisms for resisting the shortage of water during the summer, they are still the dominant feature. Since the areal coverage of the perennials is almost constant throughout the year, those of the biological soil crusts and annuals compete with each other for the remaining ground space.

The timing of the onset, peak, and senescence of each ground feature is strongly dependent on the amount and distribution of rainfall in any particular year. The current study was conducted during a year of above-average rainfall, as well as during a year of below-average, and near-average rainfall. The temporal distribution of rainfall also varies from year to year. However, the general three phenological cycles are always observed although their respective NDVI peaks are not constant over time. The soil biological crusts show a NDVI peak 1–2 months after the rain starts. The peak of the annuals is 3–4 months, and that of the perennials is 5 or more months after the rain starts.

Current ground observation can be upscaled to satellite remote sensing. The timing of the acquisition of remotely sensed data is important with regard to the phenology of vegetation and that of the soil, although so far, the latter has not received the same attention as the former. It was shown that the soil in semi-arid environments cannot always be considered to be bare, thus its spectral signature should not be considered to be constant all year long. Misinterpretation of a spectral signal can have serious consequences in remote sensing applications that are used to estimate biomass, carbon fluxes, and grazing periods, or aid the extraction of soil/rock minerals, etc. Knowing the time along the growing season, an inversion linear-mixture method can be used for estimating the relative contribution of each of the above-mentioned ground features within a single air- or space-born remote sensing system.

Concluding remarks

Three phenological cycles of natural vegetation can be separately observed in two semi-arid environments of the Northern Negev (Israel) owing to their different spectral, spatial, and temporal signatures. These cycles are those of the biological soil crusts, annuals, and perennials.

These three phenological cycles are detectable by spectral ground measurements and by calculating the weighted values of the NDVI. The weights are the product of the derived NDVI of each ground feature and the respective areal cover.

The biological soil crusts show the earliest and highest weighted NDVI peak during the rainy season. Their weighted NDVI signal also extends longer than that of the annuals.

The annuals are dominant in late winter and early spring, and the perennials in late spring and during the summer.

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