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Temporal dynamics of soil and vegetation spectral responses in a semi-arid environment

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Abstract. This paper discusses several difficulties encountered in detecting and monitoring temporal changes in vegetation using multispectral imagery from airborne or spaceborne sensors. These difficulties are due to (1) temporal change in the vegetation state; (2) temporal change in the soil/rock signature; and (3) difficulty in discriminating vegetation from soil or rock background. The seasonal dynamics of soil and vegetation was investigated over two years on permanent sample plots in a natural fenced-off area in the semi-arid region (200 mm annual average rainfall) of the Northern Negev, Israel. Results show that temporal analysis of natural vegetation in semi-arid regions should take into account three ground features—perennials, annuals, and biological soil crusts; all having phenological cycles with the same basic elements—oscillation from null (or low) to full photosynthetic status. However, these cycles occur in successive periods throughout the year. The phenological cycle of perennial plants is related to the adaptation of desert plants to scarcity of water. Annuals are green only for a relatively short period during the wet season and turn into dry organic matter during the summer. The microphytic communities (lower plants) of the biological soil crusts are rapidly affected by moisture and turn green immediately after the first rain, in a timescale of minutes. In arid environments, where the higher plants are sparse, this type of plant has considerable importance in the overall production of the greenness signal. However, crust-covered areas are visually similar to bare soil throughout the dry period. This paper concludes that a priori knowledge of the phenological changes in desert plants (lower and higher) is valuable in the interpretation of remote sensing data of arid environments. It is shown that rainfall amount and regime are the keys for understanding the dynamic processes of the different ground features. Through polynomial fitting, simple functions describing the annual variations in the NDVI of the different cover types have been formulated and validated; showing the feasibility and viability of modelling the processes. Although fluctuations in the rainfall regime between years poses a problem to designing a unique model, it is believed that such a problem can be overcome with long-term observations.

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1. Introduction

Spectral response of soil/rock and vegetation in the visible and near infrared (NIR) is probably the most popular theme for research among remote sensing scientists. In spite of a considerable number of research studies, there are still several difficulties in detecting and monitoring vegetation using multispectral imagery from airborne or spaceborne sensors. These are due to: (1) temporal change in the vegetation state; (2) temporal change in the soil/rock signature; and (3) difficulty in discriminating vegetation from soil or rock background. This research is limited to the temporal dynamics of soil and natural vegetation in a semi-arid environment.

1.1. *Temporal change in the vegetation state*

The growth stage or the phenological stage of plants (or plant communities) may result from a combination of changes in the plant leaf structure, pigments, and/or canopy area throughout the growing season. Consequently, phenology has some influence on the seasonal reflectance dynamics.

According to Lieth (1974) the term phenology is related not just to the timing of recurring physiologic processes but also to their causes, especially with regard to meteorological phenomena. In the desert environment, plants are exposed to the full impact of extreme external conditions and consequently must adapt to them. The principal adaptation that desert plants have to make is to the scarcity of water. Scarcity may occur in two ways—either by a very big difference in rainfall amount between years or different rainfall regimes throughout the rainy season. Therefore, desert plants must face the challenge of drought years and survive with little or no rain. They also must adapt in years when the temporal distribution of the rainfall amount and intensity are extremely unusual.

Water stress causes insufficient hydration of the protoplasm of the plant cell; this affects the photosynthetic activitiy of the plant, e.g. its ability to produce carbohydrates (starch and sugar). Due to insufficient production of these elements the plant may sustain some damage or even die. The adaptation of desert plants to water stress may be morphological, physiological, or behavioural in nature. Thus, the xerophytes, plants which grow in dry and hot environments, have developed a large number of mechanisms for resisting the shortage of water. A full discussion on adaptation of plants to desert conditions can be found in Evenari *et al.* (1982) and Danin (1983). However, since the detection and monitoring of vegetation by remote sensing are concerned mainly with detection of chlorophyll, this paper is restricted just to the discussion of the adaptation mechanisms of leaves and to a lesser extent also to those of the stems (rather than to those of the roots and seeds).

Different spectral vegetation indices have been proposed during the last three decades for monitoring the physiological and spatial distribution of vegetation from remote sensing data. Most indices are based upon a certain combination of the ratio between the red waveband, R, where chlorophyll causes considerable absorption of incident light, and the NIR wavelengths, which corresponds to the zone of maximum reflectance of incoming radiation by healthy green leaves due to their internal mesophyll structure. The Normalized Difference Vegetation Index (NDVI) (Rouse *et al.* 1974) is the most widely used index. It is formulated as follows:

$$NDVI = \frac{R_{\mathrm{NIR}} - R_{\mathrm{red}}}{R_{\mathrm{NIR}} + R_{\mathrm{red}}} \qquad (1)$$

where R is the reflectance value in the indicated band. This equation produces NDVI values which lie in the range of -1.0 to $+1.0$ with denser and/or healthier vegetation having higher positive values.

In this work, not much attention has been paid to differentiating among different species of desert plants. However, two categories of vegetation have been distinguished—annuals and perennials. Annual plants, in contrast to the perennials, germinate only after exposure to rain or flood water. Their life cycle is limited to the rainy season and includes stages of growing, flowering, fruiting, and dispersing seeds. During the summer they are completely dead and their above-ground parts are dry. According to Evenari *et al.* (1982) 59% of the Negev winter species are winter annuals. The number of annual species and the amount 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.

Phenological cycles for cultivated crops are usually studied for each crop type. However, in remote sensing applications for agriculture, other phenomena, such as two or three major crops growing simultaneously with different phenological cycles or several crops growing successively in the same field, are also investigated (e.g. Fischer 1994). Similar research hardly exists for natural vegetation and especially for arid environments only one phenological cycle is considered for the entire year (e.g. Justice *et al.* 1985, Tucker *et al.* 1985, Shinoda *et al.* 1995, Lambin *et al.* 1996, Rasmussen 1997).

1.2. *Temporal change in the soil/rock signature*

Most observers perceive desert and desertified landscapes as areas with sparse cover of higher plants, and this is equated with sparseness of all vegetation. In contrast to desert higher plants and with the exception of wet/dry conditions, the soil/rock background spectral signature is usually considered to be constant all year long. However, a closer examination of the desert landscapes provides a different view of the ground cover. In the absence of a dense distribution of higher plants, most 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 biological soil crusts over and within soils and rocks. The microphytes can grow on different rocky materials such as limestone, chalk, dolomite, flint, sandstones, granite, as well as on different soil types such as loess and dune sand (Friedmann and Galun 1974, Rogers 1977, Evenari *et al.* 1982, Harper and Marble 1988, West 1990, Knutsen and Metting 1991, Metting 1991, Johansen 1993, Eldridge and Greene 1994).

Desert microphytes are poikilohydrous, i.e. they are organisms capable of desiccation. They can persist under extremely dry conditions by losing a major part of their body water and desiccating to air dryness whenever water is unavailable. In this state, they are dormant and all their metabolic processes are reduced to a minimum. They are physiologically and ecologically quasi-isolated from their surroundings and capable of surviving several years of drought and high temperatures. A few minutes after wetting, they start respiring, and if light is also available, they revert to full photosynthetic activity. This hydration–dehydration cycle can be repeated innumerable times (Evenari *et al.* 1982).

Under arid and semi-arid conditions the water source for activating the microphytes is normally rain and flood water. However, rain and flood events are infrequent both spatially and temporally, and in the absence of rain and flood events it was found that the main source of water is probably dew (Evenari *et al.* 1982). It has been observed in the Israeli Negev Desert, for example, that while rainfall is restricted to a few days in winter and is unevenly distributed, the number of dew days and dew amount is highly constant (Evenari *et al.* 1982, Zangvil 1996).

From the remote sensing point of view microphytic crusts are extremely important because of their photosynthetic activity. Karnieli *et al.* (1996) showed that the spectral reflectance curves of these microphytes, when they are active, have been found to resemble those of higher plants and their NDVI values can be as high as 0.30 units. Thus, the reflectance of lower plant communities may lead to confusion in the interpretation of vegetation dynamics and overestimation of ecosystem productivity in semi-arid environments.

Consequently, in the rest of this paper the soil background will be denoted as 'crusts'. It is assumed that this term is better than 'soil' for describing the uppermost layer of the soil profile which is exposed to the remote sensor regardless of wetness conditions and biologic activity.

1.3. *Discriminating vegetation from the soil or rock background*

In many situations the ground is partially covered by vegetation. Consequently, the spectral signature contains a mixture of the vegetation which characterizes the above-ground cover and the underlying material. This phenomenon is typical in semi-desert areas that are naturally characterized by dispersed vegetation (Danin 1983). Remote sensing studies show that when the dispersed plant cover is less than 30%–40%, the satellite sensors are not capable of detecting vegetation, and the signal received shows mostly the soil background (Colwell 1974, Pearson *et al.* 1976, Huete *et al.* 1984, Elvidge and Lyon 1985, Tueller 1987, Smith *et al.* 1990). 'Mixed pixel' refers to a pixel containing more than one ground cover type (Hyde and Vesper 1983). Such pixels are the major source of inconvenience in conventional classification processing, therefore it is desirable to decompose (or 'unmix') each mixed pixel to its ground cover components (denoted as 'endmembers'). Ichoku and Karnieli (1996) reviewed different types of mixture modelling techniques, such as linear, probabilistic, geometric–optical, stochastic geometric, and fuzzy models.

The linear mixture model, which is a popular model, has been put to use in this work. It is based on the assumption that the value of the reflectance of each mixed pixel in a given band of a satellite image is a linear combination of the spectral reflectance of each endmember weighted by their respective areal proportions (e.g. Adams *et al.* 1986, Shimabukuro and Smith 1991, Quarmby *et al.* 1992, Settle and Drake 1993). Thus, the reflectance R_i of a pixel in the ith band is given by

$$R_i = \sum_{j=1}^{n} (a_{ij} x_j) + e_i, \quad \text{with } i = 1, \ldots, m \text{ and } j = 1, \ldots, n \tag{2}$$

where, a_{ij} denotes the reflectance of the jth component of the pixel in the ith spectral band; x_j is the proportion of the ith component in the pixel; e_i is the error term in the ith spectral band; m represents the number of spectral bands while n stands for the number of components in the pixel.

Equation 2 represents a system of linear equations which can be expressed in matrix notation as:

$$R = Ax + e \tag{3}$$

Equations 2 or 3 can be solved in one of several ways in order to determine the proportions x_j of the components in individual pixels. Since the proportions should sum to unity, the linear constraint, $x_1 + x_2 + ... + x_n = 1$ may be included as part of the system of equations, with the proviso that none of the proportions should be negative (i.e. $x_j \geqslant 0$). Generally, the number of unknowns should be less than or equal to the number of equations for there to be a convenient solution. This implies that the number of components n should be less than or equal to the number of bands m (or $m+1$, in the case of inclusion of the sum-to-one linear constraint). If n is strictly less than m (or $m+1$) then, x_j will be overdetermined in the system of equations, enabling it to be solved by the method of least squares (Shimabukuro and Smith 1991, Settle and Drake 1993).

2. Study area

The research site is located in the Northern Negev of Israel (31°17′N, 34°37′E), in a 2 km² hilly area (elevation varying between 75 m and 100 m above MSL) closed off to protect it from livestock grazing since 1987, seven years prior to this study. Rainfall, which only occurs in winter between November and April (later in this paper the rainfall season is also referred as 'hydrological year'), has a long-term annual average of 200 mm. Average daily temperatures are 7°C and 33°C in the winter and summer, respectively. The 200 mm isohyet is considered to form the transition zone between the semi-arid and subhumid climatic regions in Israel.

The research was conducted on a north-facing hillside with a slope of ca. 7%. The soil is loessial, about 1 m thick with 14% clay, 27% silt, and 59% sand. The salt content of the 0 cm–25 cm top soil layer is low, with an electrical conductivity of 0.4 mMho (Zaady *et al.* 1996). About 70% of the soil surface is covered by biological soil crusts (Zaady and Shachak 1994). Several different communities of such crusts were observed. Cyanobacteria (mainly *Microcoleus vaginatus, Nostoc punctiforme,* and *Chroococcus* sp.), soil lichens (*Collea* sp., composed of *Nostoc muscorum* and an undefined fungus), and two species of mosses (*Aloina bifrons* and *Crossidium crassinrve* var. *laevipilum*). The higher vegetation consists of scattered patches of *Noea mucronata* and *Atractylis serratuloides.*

3. Methodology

Three study plots, each 15 m × 5 m in size, were marked out on the north-facing hillslope in the study area. During the 20 months of research, there were a total of 13 sampling days at intervals of one or two 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:

- *Radiometric measurements:* Field measurement was conducted with the Cropscan multispectral radiometer. This radiometer is characterized by eight wavebands centered at intervals of 50 nm between 460 nm and 810 nm. The optical head (MSR87) that has 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 per cent reflectance for each waveband. Fifteen successive spectral measurements were taken on a fixed point in each of the three experimental plots. Therefore, 45 repetitive measurements were taken on each of the five sampling days during the 1994/5 rainy season. All were conducted on clear days. The 45 measurements were averaged, giving five mean spectra sets for each sampling day.

- *Above ground photographing:* A 35 mm still camera was installed on a metal tripod at 4 m height above the ground surface. The camera was mounted upside down. The tripod was displaced along the study plots between exposures such that five single colour photographs covered each plot with overlap.
- *Soil and vegetation sampling:* Leaves (and sometimes also stems) were clipped from each representative species of the higher vegetation in the study area for laboratory spectral measurements. Biological and soil crust samples were collected in petri dishes for the same purpose.

Each five-photograph set was arranged as a mosaic to create one covering each study plot. Three cross sections were drawn along the long axis of the mosaic and the ground coverage of each of the three ground features was estimated along these sections.

In the laboratory, the spectral characteristics of the leaf and biological soil crust samples were studied using the Li-Cor LI-1800 spectrometer. The instrument was fixed to 15° field of view, and spectral resolution of 2 nm wavelength spread between 400 nm and 1100 nm. Spectral analysis involved NDVI calculations according to equation 1 and linear mixture calculations according to equation 2. The latter was performed in conjunction with the per cent coverage of each of the ground features (endmembers).

4. Results

The daily distribution of rainfall during the two wet seasons is presented in table 1 and the monthly distribution is illustrated in figure 1. One might notice that the two rainy seasons are characterized by different rainfall regimes. In the first hydrological year (1994/5) the rain started on 2 November 1994 and several very high intensity events occurred during the first two months. The annual average

Table 1. Daily rainfall distribution during the two years of study.

Date	Elapsed no. days	Daily rainfall (mm)	Cumulative rainfall (mm)	Monthly total (mm)
2 November 1994	0	14.2	14.2	
7 November 1994	5	23.0	37.2	
17 November 1994	15	12.3	49.5	
25 November 1994	23	34.6	84.1	
28 November 1994	26	7.9	92.0	
30 November 1994	28	20.8	112.8	112.8
5 December 1994	33	88.0	200.8	
15 December 1994	43	5.3	206.1	
17 December 1994	45	4.1	210.2	
20 December 1994	48	2.9	213.1	100.3
8 February 1995	98	19.5	232.6	19.5
24 March 1995	142	2.5	235.1	2.5
3 April 1995	152	7.3	242.4	7.3
6 December 1995	0	18.8	18.8	
13 December 1995	7	18.4	37.2	37.2
19 January 1996	44	18.7	62.9	18.7
4 February 1996	60	21.6	84.5	21.6
26 March 1996	111	34.6	119.1	34.6

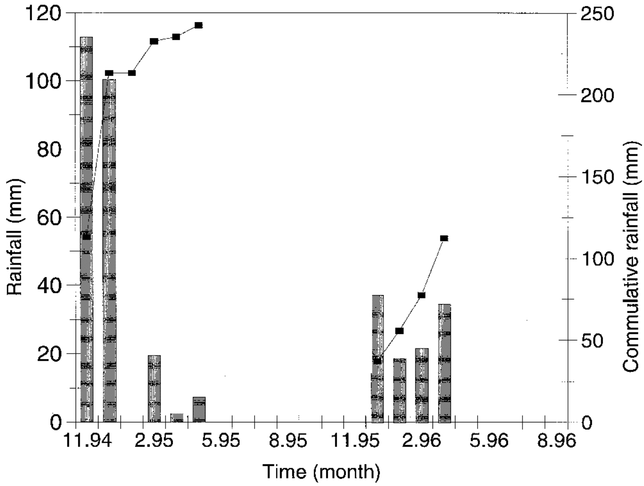


Figure 1. Monthly distribution of rainfall during the two years of research.

(200 mm) was reached relatively early (on 8 December 1994) while the rest of the season was characterized by relatively small events with relatively long dry periods between them. The 1994/5 rainy season ended on 3 April 1995 with 242.4 mm of rain, 20% above the annual average. The second hydrological year (1995/6) started relatively late, on 6 December 1995 and was characterized by only five rainy days of moderate intensity. This rainy season ended on 26 March 1996 with 119.1 mm total rainfall which is as low as 60% of the annual average.

The spectral responses of the three main ground features—biological soil crusts, perennials, and annuals—at different times of the hydrological year 1994/5 are presented in figure 2(A, B, and C) respectively. The first biological soil crusts sample was collected on 18 November 1994, after two weeks of rainfall the total of that exceeded 49 mm. It is clear that the corresponding crust spectra for this time shows a typical vegetation spectrum with high peak around 550 mm (green), trough around 680 nm (red), sharpe rise in the 700 nm (red edge), and the NIR plateau between 700 and 1100 nm wavelength. This is the signal received from the microphytic communities that covered the ground at that time. The communities of cyanobacteria, lichens and mosses (as described above) returned to full physiological activity due to the soil moisture. Consequently, they turned green and photosynthesized like higher plants. The next samples in December 1994, February and March 1995 show also the same pattern, but the red trough disappears gradually. The last samples of April, August and November 1995 are almost similar and represent a bare soil spectrum, which starts low in the blue and increases gradually towards the NIR, with no evidence of any photosynthetic activity.

The first annuals spectra, obtained two weeks after the beginning of the rainy season, shows an almost flat curve, increasing continuously from the blue region towards the NIR region, except for a slight trough in the red region. At this time of year most of the annuals had hardly germinated. One month later, and even until April, the annuals present typical green vegetation spectra. During the dry season, their spectra are flat again, increasing progressively towards the higher wavelengths, a property typical of dead or senescent vegetation (Jensen 1986, p. 159).

The perennial spectra show curves typical of green vegetation all year round.

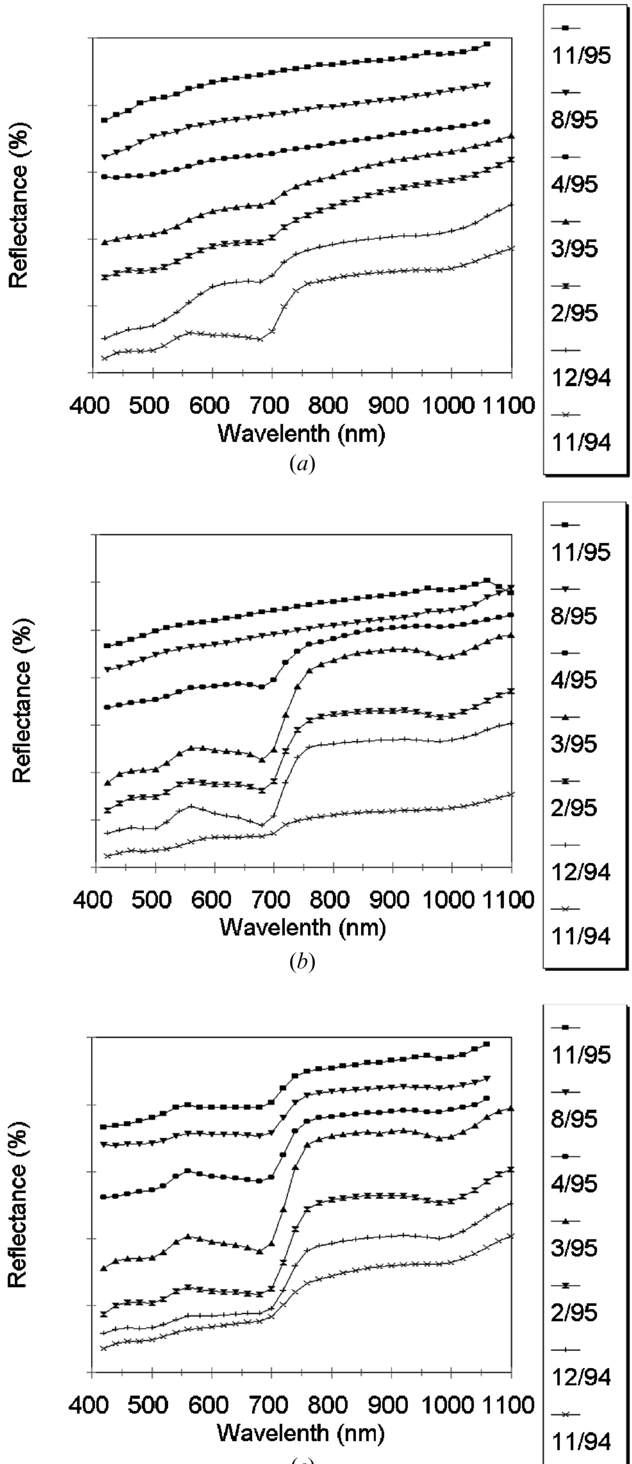


Figure 2. Yearly variations of the spectral response of ground features for 1994/5: (A) biological soil crusts; (B) annuals; (C) perennials. Each tick on the y-axis represents 10% of reflectance. However, all curves have been offset vertically for clarity.

However, until February 1995, these spectra have very shallow troughs in the red and relatively gentle slopes at the red edges. The March to August curves represent the typical green vegetation spectra while the last, November 1995, returns to the starting curve of the previous year.

Proportions of the areal coverage of the three ground features are illustrated in figure 3. The perennials show a relatively constant coverage, 30% on average with 13% coefficient of variation. Larger areal coverage of the perennials exists during the spring months due to the renewal of larger winter leaves instead of those leaves that shrunk and those shed in the summer. Biological soil crusts and annuals show significant variations throughout the year. The average areal coverage of the annuals is 20% and their coefficient of variation is the largest, 44%. They show maximum coverage in February–March (about 35%) and a minimum of 6% is November. Average areal coverage of the crusts is 50%, and the coefficient of variation is 22%. The cover of the biological soil crusts is dominant all year around; however, its coverage starts to increase in June, exceeding the maximum in November and dropping sharply in February.

NDVI values were computed from the reflectance values of each of the ground cover types based on equation 1. The mixed reflectance was calculated from equation (2) by applying the spectral laboratory reflectance and the respective proportions of areal coverage for each of the three features (endmembers). Then, the NDVI values for the mixed type were computed from these composite feature spectra. Figure 4 presents the temporal variations of the NDVI values for biological soil crusts, annuals, perennials, as well as the mixed NDVI values. The latter shows the general expected phenologic cycle–high NDVI values of about 0.30 to 0.45 units in the winter which decreases to around 0.20 units in the summer. Examining each line separately, and especially the envelope curve (upper line composed from the three individual curves of the biological soil crusts, annuals, and perennials) reveals different phenological cycles for each of the features, each having a different timing. The first peak is that of the biological soil crusts, the second of the annuals and the last is of the perennials. It should be noted that for better understanding of figure 4, interpretation has to be

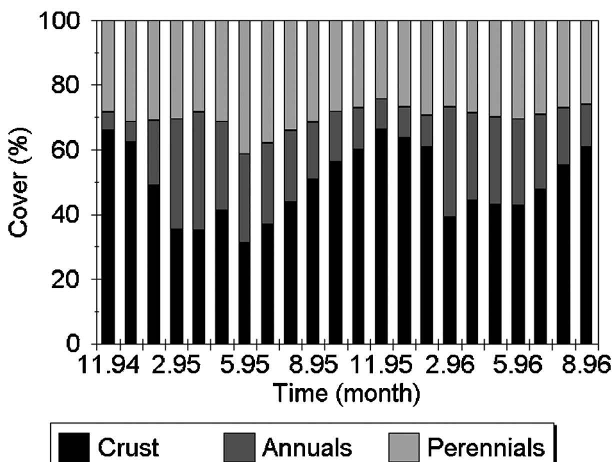


Figure 3. Bi-annual variations of the proportions of areal coverage of biological soil crusts, annuals, and perennials.

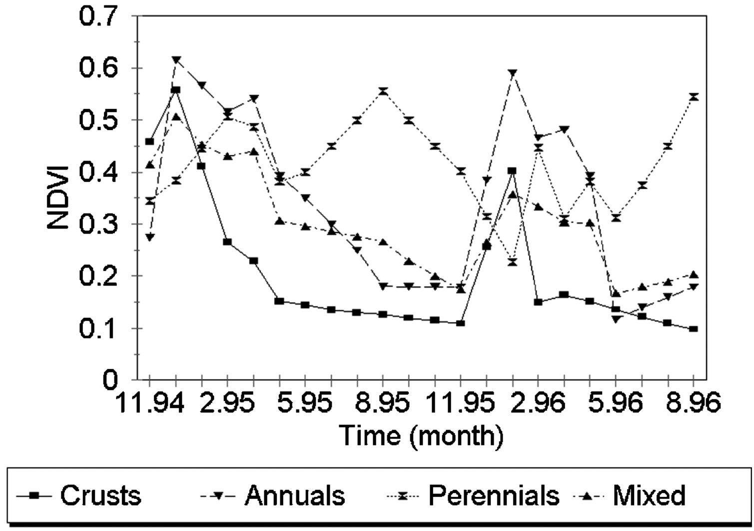


Figure 4. Bi-annual phenological cycles for the NDVI values of biological soil crusts, annuals, and perennials.

carried out with respect to the rainfall data presented in table 1 and figure 1. In the 1994/5 hydrological year, the first sampling, performed about two weeks after the heavy rains at the beginning of the season, shows high NDVI value for the biological soil crusts. This peak decreases rapidly and in its place the cycle of the annuals starts. In April the annuals cycle drops leaving the stage for the cycle of the perennials which rises and remains high through the dry season to the first rains of the next year. The 1995/6 hydrological year which was totally different in terms of the rainfall regime, started in January with two peaks, those of the biological soil crusts and the annuals, at the same time. This can be explained as due to the late rains which caused the fast development of green cover of the annuals resulting in NDVI values which are higher than those of the biological soil crusts and which actually mask the crust's spectral responses. The cycle of the perennials starts again in May 1996.

In order to verify the linear mixture model results, correlation analysis was performed between the mixed spectra derived from the laboratory measurements and 45 averaged field radiometer data for the same five days of sampling. The analysis was done only between those portions of the spectrometer spectrum which correspond to the effective range of the radiometer bands. These are: 450 nm–470 nm, 996 nm–516 nm, 550 nm–560 nm, 606 nm–616 nm, 656 nm–666 nm, 696 nm–716 nm,

Table 2. Correlation coefficients, *r*, between field radiometer measurements and the linear mixture model results, derived from laboratory spectrometer measurements for five sampling days, each averages 45 measurements.

Date	*r*
12 February 1995	0.99
12 April 1995	0.97
6 August 1995	0.95
30 November 1995	0.98
9 January 1996	0.87

756 nm–766 nm, and 810 nm–820 nm. Table 2 summarizes the results. It must be noted that the overall level of reflectance of the field radiometer data are somehow higher than those of the laboratory spectrometer measurements although they exhibit the same pattern. The high values of correlation coefficient r verifies the basic assumption of the study: the three main components—biological soil crusts, annuals, and perennials—contribute to the overall mixture reflectance in different proportions.

5. Modelling

A close look at each of the curves in figure 4 reveals that they all repeat roughly the same pattern each year, in spite of the difference in the rainfall regime. This is an indication that it is possible to produce an annual model describing the shape of the NDVI curve for each of the ground cover types. It is convenient to define a simple preliminary model using the data currently on hand.

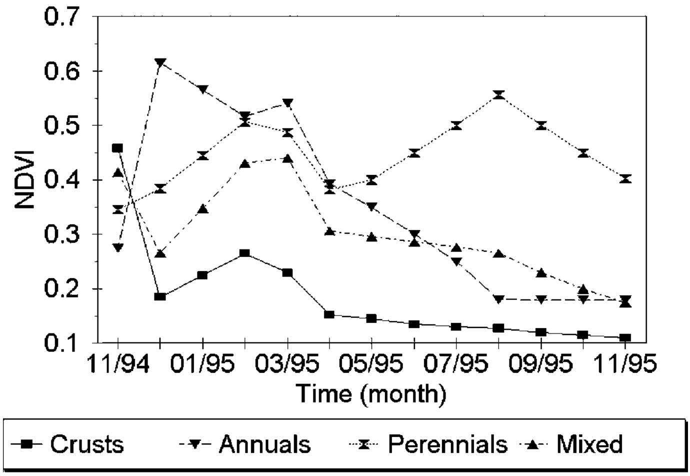
Polynomial curve fitting was performed on data covering one complete annual cycle period from November 1994 to November 1995, using χ^2 (chi-square, defined in most books on statistics) as the goodness-of-fit criterion. The procedure involved fitting low (2–5) degree polynomials on each of the curves. The coefficients of the polynomials are determined by the method of least squares and the χ^2 value for each fit is calculated. For each curve, the polynomial that yields the smallest χ^2 value is adopted as the model equation. As such, the different curves may correspond to polynomials of different degrees. The fitted polynomials for the different ground cover types and the corresponding χ^2 values are shown in table 3.

Figure 5(A, B) shows plots of the data for the annual cycle (November 1994 to November 1995), in which the upper graphs (A) represent the original data while the lower ones (B) represent the model values for the same period. In order to express the model accuracy quantitatively in the traditional way, the rms (root mean square) deviation between the original and model data was computed for each cover type. The models were then validated with the original data for the next year—November 1995 to August 1996 (as data were not available for September to November 1996), and the corresponding rms values were computed. They are a measure of how well the models for the first year fit the second year. In all cases,

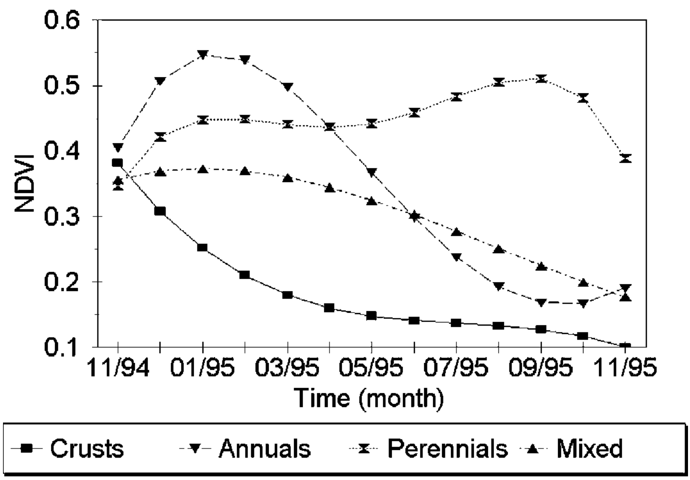
Table 3. Polynomial model functions generated from the 1994/95 NDVI data for biological soil crusts, annuals, perennials, and mixed cover types, as well as the corresponding χ^2 measurements of fit and rms deviations of model results with respect to the original data for 1994/95 and 1995/96 annual cycles.

Ground cover	Polynomial model function	Fit χ^2	rms deviation	
			1994/95	1995/96
Crusts	$y=0.5-0.1x+0.01x^2+0.0004x^3$	0.03	0.035	0.069
Annuals	$y=0.2+0.2x-0.05x^2+0.003x^3-0.00007x^4$	0.03	0.039	0.088
Perennials	$y=0.2+0.2x-0.05x^2+0.006x^3-0.0002x^4$	0.02	0.027	0.071
Mixed	$y=0.3+0.3x-0.005^2+0.0002x^3$	0.03	0.036	0.067

x represents the serial number of the month (with November = 1, December = 2, etc.), and y designates the modelled NDVI value.



(*a*)



(*b*)

Figure 5. Graphs of the (*a*) original and (*b*) modelled NDVI for a single complete annual cycle—November 1994 to November 1995.

rms was computed as follows:

$$\mathrm{rms} = \sqrt{\frac{\Sigma_{i=1}^{N}\{y_i - y(x_i)\}^2}{N}} \tag{4}$$

where for a given cover type, y_i is the original NDVI value for month i, $y(x_i)$ is the model computed NDVI value for the same month, x_i is the numeric value representing the month according to the convention used in the correct model, and N is the number of values (months) in each data set. All the computed rms values are shown in table 3 against their respective cover types. Although obviously the models do not fit the second year's data as accurately as they fit the first year's data (from which they were generated), over the fits are fairly good, showing similarity of trends between the two years for all cover types. This is particularly encouraging considering the large difference between the rainfall regimes of the two annual cycles.

6. Discussion

It is shown that the temporal analysis of natural vegetation in semi-arid regions should take into account three ground features—perennials, annuals and biological soil crusts—in a way that is not commonly considered either in agricultural areas or in humid regions. Desert perennial plants have to adapt themselves to scarcity of water. Since the adaptation may be morphological, physiological, or behavioural in nature it affects both the pigment concentration and/or the leaf structure. Consequently, the phenology of perennials exhibits different spectral responses throughout the year. Annual plants are green only for a relatively short period during the wet season, but only after water has been available to them. During the dry period they are completely dead and what remains of their above-ground parts produces the spectral signal of dry organic matter. The microphytic communities of the biological soil crusts are very sensitive to moisture, and turn green immediately after the first rain. This type of plants has considerable importance in the overall production of greenness signal in arid environments where the higher plants are sparse. However, biological soil crusts should be considered as bare soil throughout the dry period.

A combined observation of these three ground features demonstrates three phenological cycles that have the same basic elements—oscillation from null (or low) to full photosynthetic status. The cycles do not overlap. The microphytes 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, their spectral signal is especially important at the beginning of the rainy season when the annuals have not yet germinated and the perennials have hardly sprouted. Next, the annuals cover the ground, but only after a month from the beginning of rains do they reach their maximum coverage, which remains high for about four months. Different annuals can germinate at different times throughout the wet season and therefore might cause more than one peak of greenness, as evidenced from figure 4. Only when the annuals dry out do the perennials become the dominant plants. Although during the summer time they apply their adaptation mechanisms to the resistance of the shortage of water, 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 space.

Indeed, this paper shows that a priori knowledge of the phenological changes in plants is a valuable tool in the remote sensing interpretation of ground features—identification of per cent coverage of vegetation and distinction between different plant communities. It can be concluded that the timing of the acquisition of remotely sensed data is important in relation to both the phenology of vegetation and that of the soil, although the latter has not received the same attention to data. It was shown that the soil in semi-arid environments cannot always be considered as bare soil and its spectral signature should not be considered constant all year long. The misinterpretation of spectral signals can have serious consequences in relation to remote sensing applications in the estimation of biomass, carbon fluxes, grazing periods, in the extraction of soil/rock minerals, and more.

Uncertainty in the rainfall regime still poses a problem. It is shown that rainfall amount and regime is the key for understanding the dynamic processes of the different ground features. Unfortunately, neither of the two rainy seasons studied demonstrates the annual average rainfall amount nor the common temporal distribution of the rainy days. The most visible effect of the late rainfall that occurred in the 1995/6 hydrological year is that the biological soil crusts' NDVI values are masked by those of the annuals (figure 4). It is assumed that under normal conditions the phenological cycle of the microphytes would be longer than was the case in the beginning of the 1994/5 rainy season. This effect cannot be observed due to the extreme concentration of rainfall events during November–December 1994. In summary, the extreme fluctuations between years show that it might be difficult to design a unique model for arid environments without taking the rainfall regime into consideration.

The importance of establishing models of annual reflectance (or NDVI) trends for the ground cover types treated in this paper as well as others has already been emphasized. Moreover, the results of the polynomial modelling performed here suggest its viability. However, in order to minimize the effect of fluctuating rainfall regimes as indicated above, there is need to acquire data over many years. This will enable more elaborate mathematical models to be formulated, taking different factors into account. For instance, Fischer (1994) performed 'double logistic' modelling and generated a function describing the seasonal (annual) variations of NDVI for winter wheat, corn, spring barley, and sugarbeets. Similarly, suitable modelling approaches could be used to generate functions describing the annual reflectance patterns of natural arid and semi-arid landscapes.

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