Multidate adaptive unmixing and its application to analysis of ecosystem transitions along a climatic gradient

Maxim Shoshany a,*, Tal Svoray b

a Environmental Information Laboratory, Bar-Ilan University, Ramat Gan 52900, Israel
b Dept. of Geography and Environmental Development & Dept. of Information Systems Engineering, Ben-Gurion University of the Negev; Beer-Sheva, Israel 84105

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Abstract

Environmental heterogeneity characterizes Mediterranean regions and zones of transition between humid and arid climates. Mapping of shrubs, dwarf shrubs, and herbaceous growth is of primary importance for understanding ecosystem function in these vulnerable environments. High spatial fragmentation in these three cover types implies that they are highly mixed at spatial resolutions greater than a few meters. A new methodology is presented which uses phenological differences between shrubs, dwarf shrubs, and herbs to map fractions of each at subpixel scales. To account for seasonal differences, Landsat images acquired at the end of winter and at the beginning and end of summer were analyzed. Differentiation between elementary vegetation and soil cover fractions was achieved using a well-known multispectral unmixing technique in an adaptive way. In this way, an image-based zonal partition facilitated spectral end-members selection according to seasonal variations and to climatic/biotic/lithologic transitions. The methodology was then applied to three Landsat images of an area representing a climatic gradient in the center of Israel. New maps of spatial changes in vegetation cover fractions along the climatic gradient were produced. An important element of the new data relates to the distribution of dwarf shrubs in general, and of Sacroproterium spinosum in particular. These dwarf shrubs are of major ecological significance in countries of the eastern part of the Mediterranean Basin due to their rapid invasion into abandoned fields and burnt areas. © 2002 Elsevier Science Inc. All rights reserved.

1. Introduction

Mediterranean regions and other transition zones between humid and arid climates are characterized by high sensitivity to global warming, desertification processes, and land-use transformations due to expanding urbanization. High rates of spatial and temporal changes are among the most salient properties of these environments (Di Castri, 1981), resulting in “shifting mosaics” landscapes: patch patterns representing ecosystem responses to varying habitat conditions and cycles of disturbance and recovery. It is this heterogeneity which modulates changes, stabilizes and maintains the recovery potential of these ecosystems. Identification of significant landscape transformations and understanding the dynamics of natural vegetation patterns and their relationships with ecosystem function (Blondel & Aronson, 1995) need to be based on detailed spatial–temporal information over wide regions. Furthermore, for these purposes, such information must refer to plant communities’ compositions rather than mixed vegetation categories.

Average yearly rates of natural vegetation change between 1% and 2%, which were recorded in the Mediterranean Basin (Barbero, Bonin, Loisel, & Quezel, 1990; Blondel & Aronson, 1995; Le Houerou, 1990), further emphasize the importance of wide scale and frequent monitoring scheme. However, according to the International Geosphere Biosphere Program (IGBP), widening the scope of investigation into changes in vegetation beyond local regions necessitates “… a generalized patch model which is able to simulate the dynamics of all ecosystem types” (Shugart & Smith, 1996). This model has categorical and scale implications. The use of a physiognomic classification scheme based on the morphological, structural, and seasonal periodicity properties of plant communities (Kuchler & Zonnenveld, 1988) is instrumental for this purpose. Vegetation formations of trees, shrubs, dwarf shrubs, and herbaceous growth represent the main physiognomic categories which are highly mixed in Mediterranean environments forming a variety of patch types. These patches vary from...
elementary ecological units of individual plants (often less than 1 m in size) up to landscape units of between few square meters and few hectares, composed of complex patterns of such elementary units.

In view of this spatio-temporal complexity, the relatively low resolution provided by NOAA, Landsat, and SPOT imagery, it is obvious that their pixels represent heterogeneous physiognomous compositions. Mapping these compositions, which are determined by the relative cover fractions of the four vegetation formations for each image pixel, increases the ecological information content provided by these imagery significantly. Such information is consistent between imagery of different resolutions and furthermore allows ecologists to link it with data, which are traditionally collected in the field. Remote sensing studies have addressed the objective of mapping subpixel vegetation fractions. However, two important questions still require attention: (1) Do existing methods allow differentiation between subpixel fractions of different physiognomous types from satellite images? (2) Are these methods suitable for Mediterranean environments?

2. Remote sensing studies of vegetation compositions

The need to provide subpixel proportions of land-surface elements in general, and of vegetation components in particular, is well reflected in the remote sensing literature (e.g., Chilar et al., 2000). A substantial part of this work was conducted in Mediterranean regions using airborne scanners (Shoshany, 2000) such as the Airborne Visible/Infrared Imaging spectrometer (AVIRIS). The advantages of these scanners stem from their high spatial and spectral resolutions (224 wavelength bands, between 0.4 and 2.5 μm for the AVIRIS). Most of the existing studies were involved with unmixing elementary surface cover types such as green vegetation, nonphotosynthetic vegetation, soil, and shade (e.g., Asner & Lobell, 2000; Gao, Huete, Ni, & Miura, 2000; Roberts, Green, & Adams, 1997; Roberts, Smith, & Adams, 1993). However, only few have attempted unmixing of different vegetation formations due to their high within- and between-spectral heterogeneity (exemplified in Fig. 4 for our study area), and consequently developed composite processing strategies. Lacaze et al. (1996) optimized endmember selection in an adaptive manner, while “scanning” the image area. Ustin, Hart, Duan, and Scheer (1996) developed a two-stage approach: during the first stage, pixel fractions of four fixed end-members were selected (green foliage, dry grass, soil, and shade) and during the second stage, these fractions facilitated identification of grass, oak, chaparral, and riparian vegetation classes. Roberts et al. (1998) developed a new technique of multiple end-member spectral mixture, which enabled separation between seven evergreen classes and nine drought deciduous classes of the chaparral vegetation. Existing satellite remote sensing studies in arid and semiarid regions have used multispectral unmixing techniques since the early works of Pech, Graetz, and Davis (1986), and Smith, Ustin, Adams, and Gillispie (1990), wherein vegetation fractions were quantified as the proportional vegetation cover, relative to the soil and rock fractions. One possibility for overcoming the limitations due to the low spectral resolution of available satellite sensors was presented in the work of Maselli, Rodolfi, and Conese (1996), who used fuzzy membership grades (“a posteriori probabilities of a pixel to be assigned to the classes considered”) as indicators of cover proportions. This approach was assessed on degraded (moving window averaging) Landsat TM images of the Sieve River basin area in central Italy. The results demonstrated better separation between three forest classes (coniferous, beech, and mixed deciduous) than hard classification methods which impose one cover class per image pixel.

A different approach for overcoming spectral resolution limitations may be the use of the phenological characteristics of the different vegetation formations. Numerous global and regional studies that use multitemporal satellite data have been reported (Benedetti, Rossini, & Taddei, 1994; Ehrlich & Lambin, 1996; Eidenshink, 1992; Justice, Townshend, Holben, & Tucker, 1985; Lloyd, 1990; Lobo, Ibanez Marti, & Carrera Gimenez-Cassina, 1997; Loveland et al., 1995; Moody & Johnson, 2001; Reed et al., 1994). Most of these studies were based on vegetation indices derived from NOAA AVHRR images. The common mapping principle is that inherent relationships exist between vegetation types, their environmental controlling factors, and their seasonal index variations. The most commonly used methodology for identifying vegetation forms is based on phenological parameterizations such as average, integrated, and the difference between maximum and minimum vegetation index values (e.g., Justice et al., 1985; Reed et al., 1994). In a recent work, Moody and Johnson have analyzed the cyclic pattern of seasonal NDVI changes and parameterized them by the first and second harmonics of the Discrete Fourier Transform. Classification of the raw seasonal indices variations and combinations of phenological parameterizations was performed using various techniques resulting in different numbers of classes, which exceeded the number of vegetation formations. In many of these studies, the phenological classes were defined as mixture classes with reference to the dominant formations, for example: wooded grasslands, closed and open shrublands (Friedl & Brodley, 1997), and a mixture class of grasses and shrubs (Peters, Eve, Holt, & Whitford, 1997).

Assessments of the above reported studies of both spectral unmixing and phenological parameterizations suggest that their methodologies mainly suit cases where proportions of the mixture components might be regarded as relatively stable in wide areas. However, as discussed earlier, this is not the case in Mediterranean regions and other climatic transition zones, where patches of vegetation compositions vary dynamically in response to variations in the local habitat conditions. Most of the existing spectral
unmixing studies utilized a single date monitoring. When this strategy is implemented in Mediterranean regions, special concern must be given to the ecological interpretation of the resulting data, due to the high seasonal and interseasonal variations in rainfall and temperature. Between the few existing studies that assessed phenological differences in unmixed fractions, Roberts et al. (1997) have showed that they are most significant especially for the green vegetation fraction. The need for both spatial and seasonal adjustments (Justice et al., 1985; Reed et al., 1994) in phenomenological parameterizations is therefore inevitable when attempting wide regions’ vegetation mapping.

In comparing six common global and land cover data sets (e.g., IGBP DISCover, Simple Biosphere Models 1&2), Loveland and Brown (1999) have reported a significant agreement in forest area between the maps, but disagreements in the location and area mapped as shrubs and grasslands. These results are not surprising for two reasons: there is a missing class of dwarf shrubs and there is a substantial amount of mixing classes of shrubs, dwarf shrubs, and grasses (with bare soil and rocks as well). In Mediterranean regions, dwarf shrubs are of major ecological importance as they consist more than 15% of the total flora of these regions (according to data provided by Blondel and Aronson, 1995 for the Mediterranean Basin). Furthermore, one of the dwarf shrub species, Sarcopoterium spinosum, which is highly competitive under conditions of overgrazing and fire, was found to spread widely in the eastern Mediterranean Basin during the last 30 years, resulting in a significant loss of primary productivity (Arianoutsou-Faraggitiak & Margaris, 1981; Giourga, Margaris, & Vokou, 1998). The S. spinosum, which is mentioned also in the Bible [Book of Kohelet (Ecclesiastes), Chapter 7], consists of a distinctive stage in the vegetation succession following disturbance (Perevolotsky & Polak, 2001) and is most widespread in its invasion into abandoned fields. As discussed by Shoshany (2000), dwarf shrubs in general and S. spinosum in particular have attracted only very limited attention in the existing satellite remote sensing studies.

The first objective of this paper was to develop a method which will enable the determination of satellite image sub-pixel physiognomic compositions in areas of varying environmental conditions. The second objective was to assess spatial variation of subpixel physiognomic compositions with reference to ecosystem structure along a climatic gradient in Israel with special attention to S. spinosum distribution.

3. Study area

This study was conducted along a transect between two sites (Fig. 1), representing the wide range of habitat conditions existing in this region. The northern site of the Avisur Highland (34°55' E, 31°39' N) is located at the foothills of the Judean Mountains, at an elevation of 388 m above sea level, on brown rendzina soil on Eocene chalk (Dan, 1988). This combination of soil and lithology (with varying depth and stone cover) characterizes most of the area on this gradient. The climate is Mediterranean, with a mean annual temperature of 19.8 °C (Max. 24.9 °C and Min. 14.7 °C) and 450 mm mean annual precipitation, falling mostly in winter. The rainy season begins in October–November and ends in April. Summers are hot and are characterized by at least 5 months of dry weather. According to Sharon and Engart (1998), rainfall in this site during 1995 (year of data collection for this research) was close to the 1960–1990 average. The site is in the Mediterranean phytogeographical region and the vegetation of this area varies from maquis (shrublands) to dwarf shrublands. The growing season of the vegetation is closely associated with the distribution of rainfall. Germination of annuals and regrowth of most perennials occurs soon after the first rains.

The southern site of the Goral Hills, near Lehavim (34°45' E, 31°20' N), is located at an elevation of 280 m above sea level, on light lithosol on Cenoman hard limestone and chalk (Dan, 1988). The climate is also Mediterranean, with a mean annual temperature of 20.5 °C (Max. 27.5 °C and Min. 12.5 °C) and 250 mm mean annual rainfall. According to Sharon and Engart (1998), rainfall in this site during 1995 (year of data collection for this research) was approximately 80% of the 1960–1990 average. Vegetation is composed of species from the Mediterranean, Irano-Turanian, and Saharo-Arabian (desert) phytogeographical regions. The dwarf-shrub community develops a diffuse pattern steppe-like landscape.

The main phytogeographical study of this region was conducted by Danin (1988) and Sapir (1977) during the 1960s and 1970s and has not been updated since then on a regional scale. Six vegetation associations were mapped north of the Lehavim site (Fig. 1). These vegetation associations are termed according to the dominant or climax species, which was accompanied by various proportions of other plants.

A study of landscape recovery as a result of reduced grazing intensities in the Avisur highland using historical air-photographs (Shoshany, in press) indicated rapid regrowth of shrubs on north-facing slopes, mainly since the 1960s, and massive penetration of S. spinosum into abandoned fields along the valleys. The extent of this type of land transformation and its magnitude over the entire climatic gradient zone is not known, but at least suggests that significant differences between the maps produced in the early 1970s and today may be expected. In view of the fact that such a phytogeographical study has not been repeated since the 1970s despite the magnitude of potential land transformations, the need for cost-effective adequate remote sensing mapping techniques is emphasized. This is true, although phytogeographical studies differ substantially from remote sensing both methodologically and in their information content (Shoshany, Kutiel, & Lavee, 1996).
This study area may be regarded then as representing wide Mediterranean regions both from ecological and climatological points of view. The wide spread of dwarf shrubs in general and *S. spinosum* in particular at the eastern parts of the Mediterranean Basin and its ecological consequences is discussed for example by Arianoutsou-Faraggitaki and Margaris (1981), Giourga et al. (1998), and Margaris (1984). Similar climatic conditions to those found here exist both in North Africa countries of Libya, Algeria, and Morocco and in the Southern European Mediterranean countries of Spain and Greece.

4. Satellite data processing

Three Landsat scenes of the research area were selected from images available for 1995 (Table 1). The images were radiometrically calibrated (TM Channels 1 to 5) in the following manner:

1. Digital values appearing in the image at the end of the summer were transformed into percent reflectance values using the empirical line method (Dwyer, Kruse, & Lefkoff, 1995; Elvidge & Portigal, 1990; Roberts, Yamaguchi, & Lyon, 1985; Shoshany, Kutiel, Lavee, & Eichler, 1994).

Table 1

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Spectral bands</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat TM</td>
<td>1,2,3,4,5</td>
<td>29.3.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>17.6.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.10.95</td>
</tr>
</tbody>
</table>

Fig. 1. A location map of the climatic gradient zone in Central Israel together with the phytogeographical map modified from Danin (1988) and Sapir (1977).
This was done based on field measurements carried out using the CROPSCAN and FieldSpec radiometers (Jarmer, Lavee, & Hill, 1996) from stable targets: water bodies and highly reflective limestone bare rock areas.

(2) Radiometric rectification of the other two images to the end of the summer image using Hall, Strebel, Nickeson, and Goetz (1991) method based on the identification of a set of radiometric control points representing almost no temporal variation.

The images were geometrically corrected with 0.5 pixel RMS errors, based on 50 ground control points, through a first-order transformation. Reference points were derived from 1:50,000 topographic maps and from points measured in the field using differential Global Positioning System (GPS). Resampling of the images’ pixels was carried out with $25 \times 25$-m pixel size to facilitate simpler data integration with other information layers such as topographic data with 50-m resolution.

5. Field campaign

The field campaign was supervised and executed by field botanists from the Department of Surveying and Mapping of the Israeli Ministry of Agriculture. Analysis of aerial photographs allowed identification of 30 study sites representing a wide variety of vegetation distribution patterns along the gradient. These sites consist of slope units extending over an average of 5 ha. While heterogeneous vegetation cover characterized half of the slopes, the other half exhibited combined landscape units dominated by a single vegetation formation. Based on common ecological vegetation surveying techniques (Greig-Smith, 1967; Kuchler & Zonenveld, 1988; Mueller-Dombois & Ellenberg, 1974), land cover compositions were estimated quantitatively along transects which were marked across each of the slope units. The following cover proportions were estimated: (1) physiognomic categories of herbaceous annuals and perennials (dominant species), dry matter, and shrubs in three height categories; and (2) rock and soil cover. The location and pattern of the field survey at each site were designed to best represent the slope vegetation and to allow synchronization with the images’ data.

The survey methodology at each site was carried out utilizing two sampling techniques (Fig. 2):

- Detailed sampling along a central transect, 100 m length: the cover type was read every 50 cm using a slender bar positioned exactly vertical to the ground at each point. The resulting 200 points per transect were grouped into four sections and averaged to form a single estimate per each pixel along the transect.
- Visual estimation along two parallel transects at a distance of 50 m at both sides of the central transect. Cover proportions at each of the four circular areas along these transects were estimated twice by three surveyors and their results were averaged to best represent surface cover variation.

Using differential GPS with 1-m accuracy, it was possible to make geometric adjustments between the sampling design and array of the Landsat TM 12 image pixels. A wide range of fraction combinations was obtained with a considerable number of cases representing various forms of spatial mixing of two and three physiognomic categories. The field campaigns were carried out within 2 weeks of the image acquisition dates, mainly for assessing changes in the herbaceous cover.

6. Methodology

The methodology developed here implements environmental knowledge (Cohen & Shoshany, in press) in its inferential logical structure. Inherent relationships existing between vegetation types, environmental controlling factors, and seasonal multispectral changes are implemented within the algorithm, aimed at determining subpixel physiognomic compositions. It is hypothesized that these compositions can be inferred from differences in generalized cover fractions (rock, soil, and vegetation), at critical times between seasonal changes. Images’ data processing is then combined by the following two stages of generalized vegetation cover
fractions’ analysis and physiognomic fractions determination by utilizing phenological logic.

6.1. Stage 1: Adaptive unmixing of generalized cover fractions

A linear unmixing method was applied here since spectral differences between green vegetation and bare soil/rock surface components are substantial and as this technique was shown to be adequate for regions of similar environmental conditions (see, e.g., Adams, Smith, & Johnson, 1986; Drake, Mackin, & Settle, 1999; Garcia-Haro, Gilabert, & Melia, 1996; Gilabert, Garcia-Haro, & Melia, 2000). Pixel fractions were then determined by solving the following equation (based on the Gong, Miller, Freemantle, & Chen, 1991) algorithm as compiled by the spectral unmixing module of the PCI software (Eq. (1)):

$$R_k = (f_{\text{rock}} R_{\text{rock},k}) + (f_{\text{soil}} R_{\text{soil},k}) + (f_{\text{vegetation}} R_{\text{vegetation},k}) + e_k$$

where the different $R$'s represent the spectral reflectance of end-members at the corresponding wavebands $k$, the $f$'s are their corresponding fractions and $e$ is the residuals' and noise component. Results were then normalized to ensure that the fractions add up to 1 (for each date).

Successful application of this technique depends to a large extent on the selection of appropriate spectral end-members. The number of spectral channels provided by satellite sensor systems forms a severe limitation on the number of end-members. Consequently, these end-members are most limited in representing soil and vegetation variations, especially in areas of high spatio-temporal change such as found along climatic gradients. Image pixels corresponding to field sites with high vegetation cover of a single physiognomic type and homogenous bare surfaces of soil and rock cover comprised the main source for the image end-member sets (Smith et al., 1990). The following concerns must then be addressed:

- Spatial (regional) extent of generalized green vegetation signatures.
- Spectral differences between vegetation formations.
- Temporal (seasonal) variations in the spatial vegetation signatures and vegetation formations.

These concerns and the improved results obtained by composite processing techniques (Lacaze et al., 1996; Ustin et al., 1996) have led us to the development of an adaptive methodology whereby a zonal partition of the climatic gradient area facilitated selection of different end-member sets for each zone for each of the image acquisition dates.

6.1.1. Zonal partitioning

Assumptions of characteristic relationships between environmental conditions, vegetation patterns, soil characteristics, and spectral properties of these surface components are fundamental in this approach. Multispectral classification may then assist in revealing the regional structure and allowing its partition into zones of characteristic combinations of spectral end-members. The Iterative Self Organization Data Analysis algorithm (ISODATA) unsupervised clustering technique (Erdas, 1996) was applied for this purpose. A set of 12 spectral bands, composed of six Landsat TM bands of June and six of November 1995, established the database for implementing this technique. Such a combination of dates represents the best separation between soil types (as they reach maximal exposure) and between dwarf shrubs and shrubs. Classification results revealed the presence of a sharp boundary between the humid and the semiarid zones (Fig. 3). This result is consistent with previous remote sensing studies of another climatic gradient in this region (Shoshany, Kutiel, & Lavee, 1995; Shoshany et al, 1996) and with the boundary between dwarf shrubs and shrub units in maps presented by Danin (1988) (Fig. 1).

6.1.2. End-members selection

Image end-members (Smith et al., 1990), rather than field measured spectra, were utilized here for two reasons: firstly, since the aim of the unmixing is at deriving generalized vegetation cover fractions; and secondly, due to the high spectral heterogeneity of the different vegetation formations. As presented in Fig. 4, such spectral heterogeneity is high both within a single plant (Fig. 4a) and between physiog-
nomic types (Fig. 4b). Limitations on the number of end-members, which are set following the use of the five calibrated bands of the Landsat TM, have led to a preliminary assessment of the possibility of excluding shadow and dry matter end-member types from the unmixing process. By utilizing supervised classification, the spatial distribution of predominantly shadowed pixels was found to consist of less than 3% of the image area (with a very scattered pattern) and that they are almost absent in areas of high vegetation cover. Since internal shadow is an inherent property of physiognomic types as a result of its close relationships with their three-dimensional structure, it was decided here to avoid unmixing the shadow fraction on one hand and to exclude from the processing the full shadow pixels on the other hand. Field spectral measurement revealed that dry vegetation matter is having a spectral signature very similar to that of soil, and is therefore represented by the soil end-member.

Image end-member sets for the three dates were derived from the same image pixels corresponding to field sites with

Fig. 4. (a) Spectral reflectance heterogeneity measured within a single S. spinosum shrub. (b) Overlap of spectral reflectance variations between the main vegetation formations as derived from field measurements using the CropScan radiometer (integrated to Landsat TM bands). Upper and lower boundaries represent the range of signatures for each vegetation formation.
high vegetation cover of a single vegetation formation and homogenous bare surfaces of soil and rock cover. Four end-members were selected for each zone and each image acquisition date (Fig. 5): two for vegetation (except for the end of the summer with one vegetation end-member), one for soil, and one for bare rock. Bare rock and soils in both zones were quite stable between dates and soil (light lithosol) in the southern zone was found to be most similar to the bare rock end-member. End-members of herbaceous growth and dwarf shrubs had varied significantly both between the zones and between dates, representing their high responsivity to rainfall fluctuations. Shrublands in the northern zone and Pine plantations in the south were relatively stable except for the pines at end of the summer when their reflectance in the near-infrared decreased considerably. The wide overlap between the spectral signatures of the different vegetation formations as measured in the field (Fig. 4) provides an indication for limitations on their utilization for detecting vegetation formations. However, the distinctive differences between the vegetation end-members between the zones and between dates, representing their high responsivity to rainfall fluctuations. Shrublands in the northern zone and Pine plantations in the south were relatively stable except for the pines at end of the summer when their reflectance in the near-infrared decreased considerably. The wide overlap between the spectral signatures of the different vegetation formations as measured in the field (Fig. 4) provides an indication for limitations on their utilization for detecting vegetation formations. However, the distinctive differences between the vegetation end-members
suggest that these end-members may represent a substantial portion of this spectral heterogeneity and may therefore serve the purpose of determining the generalized vegetation cover by adding the corresponding fractions. The relative vegetation cover at the three dates provides the input required for the phenological analysis.

6.2. Stage 2: Implementation of phenological logic

The phytophenology of Mediterranean regions is primarily determined by the seasonal variation of rainfall and solar radiation intensity. Assessment of phytophenologies of different dwarf shrubs and shrubs (from Orshan, 1989) indicates that they share the following generalized characteristics:

- Flower bud formation from the end of December to April
- Flowering from March to May
- Dolichoblast vegetative growth and fruits setting from March to June (dwarf shrubs) and from March to September (shrubs)
- Leaf shedding of dolichoblasts from March to July.

A study of above-ground Herbaceous biomass growth in Lehavim site (Ungar et al., 1999), under three grazing intensities in years of low and high precipitation, indicates that the highest primary productivity occurs from the beginning of March to mid-May. From these typical cyclic pattern, it is possible to suggest that beyond precipitation variations between years, there are at least three common climatically dependent features of seasonal vegetation dynamics, these are:

- At the end of the winter both herbaceous and woody vegetation reach their maximal net primary production (NPP), which is expressed by the highest annual green biomass accumulation.
- Green vegetation at the end of the summer is composed of leaves of evergreen sclerophyll shrubs and trees that can survive the long dry and hot summer due to their developed root system and favor habitat conditions that have evolved in their close vicinity.
- Differences in green biomass between herbaceous growth and dwarf shrubs are most pronounced at the end of the spring/beginning of summer since the spring is characterized by almost no rain. Much higher drying rates of herbaceous growth during the spring relative to those of dwarf shrubs are responsible for these differences at that seasonal stage (Shoshany et al., 1994, 1995, 1996), while in mid and late summer both vegetation forms are almost completely dry.

Fig. 6. A schematic diagram of the Phenological Subtraction Methodology PSM for physiognomic compositions’ resolution using generalized vegetation cover fractions derived from the application multidate spectral unmixing.
A Phenological Subtraction Methodology (PSM) was then developed, implementing these phytophenological differences for resolving physiognomic compositions by subtracting the relative green vegetation fractions from the three dates (Fig. 6):

- Shrubs’ fractions are informed from the generalized vegetation cover proportion at the end of the summer.
- Herbaceous growth fraction is obtained by subtracting the late spring vegetation fraction from the winter vegetation fraction.
- Dwarf shrubs fraction is determined by subtracting the end of the summer vegetation fraction from that of the end of the spring (June–November).

By utilizing the generalized vegetation cover fractions determined for the three dates, the relative subpixel proportion of each of the three vegetation formations were retrieved for the whole study area following the implementation of the PSM-based algorithm.

7. Retrieval accuracy assessment

For the following vegetation formations, the accuracy of retrievals was determined by regressing field estimates against retrieved cover (estimated using the zonal temporal adjusted unmixing strategy in the PSM algorithm). The results demonstrate a strong linear correlation between the field estimated and retrieved surface covers of herbaceous growth, shrubs, dwarf shrubs, and soil/rock (Fig. 7). Slope coefficients were found to indicate relationships close to 1:1. This finding was strengthened by the relatively low mean square deviations (RMSD) from the field estimates: between 4% and 9%. This range is considered satisfactory when taking the high variability of fraction compositions along the climatic gradient region into account. The results for each of the cover fractions are as follows:

- Herbaceous growth cover estimates were highly correlated with field estimated values at an RMSD of 9%. Highest deviations were observed in the lowest cover range (0–25% cover), where most of the distant points within this range demonstrated overestimation. This might be due to confusion of herbaceous vegetation with dwarf shrubs. The main source for underestimation in the lower range may be the strong effect of soil background radiation in areas of sparse vegetation cover, such as the southern part of the study area.
- Shrub cover estimates were correlated with field estimated values at an RMSD of 4%. In general, high accuracy was achieved in most parts of the range. The main reason for this high accuracy is the unique and very strong multi-temporal signature of evergreen shrubs compared to signatures of other vegetation formations. Highest deviations were found at the lower part of the range, with a substantial

![Fig. 7. Retrieval accuracy for vegetation formations and soil fractions according to data from field surveys.](image-url)
number of points representing overestimates. A possible explanation for this overestimation may be confusion of some dwarf shrubs that could provide a signature similar to that of the shrubs. On the other hand, due to the strong differences between the multitemporal signatures of shrubs and dwarf shrubs, errors in field estimated values may also contribute to this disparity.

- Dwarf shrub cover estimates were correlated with field estimated values at an RMSD of 6%. Better accuracy was obtained in areas of moderate to high cover. Worse accuracy was observed in areas of lower cover (0–20%). In this range, data points were widely scattered with no clear trend of over- or underestimation. Due to similarities in height and density between dwarf shrubs and herbaceous vegetation, the source of error for underestimation in the case of dwarf shrubs could also be soil background radiation, whereas points of overestimation may be explained by confusing herbaceous vegetation with dwarf shrubs.

- Soil cover estimates demonstrated the lowest level of accuracy among the pixel covers. The RMSD is 8% and, in contrast to the vegetation formations, higher deviations of data points were found in the intermediate range of 40–60%. The source of higher confusion in the intermediate range is not yet clear and requires further study.

A synergy of the results presented above may lead to the following conclusions:

Physiognomic cover estimates demonstrate less accuracy in the lower part of the cover range (0–20%). This phenomenon is clearly shown in a few cases where cover estimates of 20% corresponded to field estimates of 0%, and vice versa. In contrast, higher inaccuracies of soil cover estimates were observed in the 20–50% range. In other words, below 20% relative cover, this methodology yields lower relative accuracies, probably as a result of high relative cover of dry vegetation components of spectral similarity with soil, especially in scattered patterns.

8. Assessment of regional patterns of surface cover compositions

Understanding of ecosystem changes along the gradient is difficult due to high spatial variation in both land use and natural conditions:

- Crop fields extending along the valleys stretch perpendicular to the general gradient direction;
- Pine plantation areas representing implementation of the “greening the desert” policy, undertaken by the Forestry Department of the Jewish National Fund (JNF);
- Areas of unknown histories of grazing intensities on the hilly terrain; and
- High landscape fragmentation of both vegetation and soils at various scales (Shoshany, in press): from single shrub or rock exposure of a few square meters up to slope units and patches of characteristic vegetation patterns extending over a few tens/hundreds of hectares.

A major contribution for the understanding of the ecosystems’ structure and functioning in this sensitive region might be gained by allowing systematic monitoring of vegetation cover compositions. For the purpose of presenting an ecological application of data produced by implementing the new methodology, the transition zones structure will be analyzed first according to results obtained in this study and then assessed with reference to the studies by Danin (1988) and Sapir (1977).

Mapping of physiognomic compositions was achieved by representing them as color composites (Fig. 8) of shrubs (red), dwarf shrubs (green), and herbaceous growth (blue). Two areas of spatial transformation and three areas of typical surface cover compositions were delineated based on visual interpretation of the color combinations. Two units of 2 × 2 km were selected within each of the five typical areas (Fig. 8) and analyzed for characterizing the differences between them. This analysis was conducted with reference to the average cover combinations (Fig. 9a) and spatial heterogeneity (Fig. 9b), according to the Shanon–Weiner Information Index (Shanon & Weiner, 1949) (Eq. (2)):

\[
I = -\sum_{i=1}^{4} p_i \ln p_i
\]

where \( p_i \) is the relative proportional area of each \( i \) of the four surface cover types.

Three zones of typical surface cover combinations and two transitional zones were characterized as follows:

8.1. Zone A

Zone A shows relatively high heterogeneity dominated by tall shrubs with an average cover of 42% and dwarf shrubs, herbaceous growth, and soil/rock with equivalent fractions of approximately 20% each. In the “Nahal Yor-esh” nature reserve, tall shrubs reach almost complete cover, while in ecosystems of controlled grazing pastures, shrub patches typically extend over a few hectares along the upper side of a narrow strip of exposed calcrete rock on north-facing slopes (Svoray, Shoshany, & Perevolotsky, 1996). The spatial extent of dwarf shrubs in this zone is defined by the clear boundaries of abandoned fields, while on slopes undergoing degradation or recovery processes, single dwarf shrubs are scattered within composite patches of shrubs, herbaceous growth, and bare soil/rock (Shoshany, in press).

8.2. Zone B

A sharp spatial decrease from an average cover of 42% in the north to less than 20% in the south, within a strip having
a width of 10 km characterizes this zone. Wide patches (up to 100 ha.) of dwarf shrub dominance can be clearly delineated, mainly on gentle slopes. Tall shrubs are limited to steep slopes or to niches in rocky terrain. Patches of herbaceous growth coincide with large areas of bare soil during the summer, where the relative plant density varies according to the annual rainfall.

8.3. Zone C

This zone presents dwarf shrub dominance (cover of over 50%) where tall shrubs and herbaceous growth cover decrease significantly compared to their cover proportions in the northern zones. On the other hand, fractions of bare soil/rock patches decrease only slightly in this zone. Such cover composition forms the landscape unit of the lowest heterogeneity along the gradient. Questions concerning processes leading toward the formation of this typical landscape and its change due to natural succession, desertification, disturbance, and ecosystem function are fundamental to the understanding of possible environmental effects due to global climatic changes and/or agricultural land abandonment.

8.4. Zone D

Zone D shows a gradual change from dwarf shrub dominance to bare soil/rocks with low herbaceous growth
cover. In this zone, dwarf shrub patches vary in size considerably, from a few hectares to single shrub patches. Heterogeneity higher than both the zone to the north and to the south suggests that it is a transitional landscape where dwarf shrubs either increase their invasion southward or desertification extends from the Negev Desert northward.

8.5. Zone E

This zone includes the northeastern boundary of the Negev desert with a dominance of desert lithosols (over 57%) with a significant decrease in the cover of dwarf shrubs (less than 35%) compared with the northern zone, forming a landscape of low heterogeneity. Intensive plantation activity was undertaken within this zone, combined with modification of the local topography by forming soil terraces parallel to the contour lines in order to accumulate runoff for watering the planted trees and shrubs.

Delineation of these five terrain units provides new information on ecosystem structure changes across areas between Mediterranean and arid climates. Existing studies of a transect representing such climatic variation in our region indicated the existence of a single transition (threshold) zone located between isoyets of 300 and 250 mm/year (Shoshany et al., 1994, 1995, 1996) which correspond to Zone D in this study. However, there is no indication of a clear transition zone from shrublands to dwarf shrublands between isoyets of 450 and 400 mm/year (Zone B in this study). Such a transition is much more significant in terms of ecosystem productivity: from average above-ground aerial biomass of 5 to 1.1 kg m$^{-2}$ according to representative values derived from a field survey in the study area (Sternberg & Shoshany, 2001a, in press), than that found in Transition Zone D, which does not necessarily imply a decrease in primary production. Spatial dynamics of dwarf shrubs in general, and S. spinosum in particular, is one of the principle components responsible for forming the structure of these transition zones and changing its primary productivity. In the next section, these findings will be analyzed with reference to the phytogeographical map of Danin (1988) and Sapir (1977).
9. A phytogeographical study of physiognomic compositions

Conceptual and methodological differences between phytogeographical and remote sensing mapping (Shoshany et al., 1996) suggest that these two sources are complementary rather than equivalent. Almost 30 years have elapsed between the ecological conditions described in the map by Danin (1988) and Sapir (1977) and the ground conditions existing at the time of acquisition of the images for the present study. For these two reasons, it is possible that as the level of similarities between the two data sources increases, the significance of the dissimilarities as indicators of temporal change also increases. The phytogeographical map was therefore superimposed on the vegetation fraction map. This allowed identification of typical physiognomic compositions as well as their boundaries (Figs. 1 and 8). Assessment of comparable units yielded the following findings:

- **Unit 1**: The shrub association of *Quercus calliprinos* comprised part of Zone A (tall shrubs dominance) and their southern boundary coincides.
- **Unit 2**: The shrub association of *Ceratonia siliqua* and *Pistacia lentiscus* is represented in two areas which are clearly defined in the fraction composition map.
- **Unit 3**: The shrub association dominated by *Rhamnus palaestinus* corresponds to Transition Zone B in terms of their north and south extent.
- **Unit 4**: The herbaceous plants community of the *Hyparrhenia hirta* could not be correlated to any of the typical vegetation fraction compositions.
- **Unit 5**: The disturbed shrubland and most clearly its western boundary could be delineated in the vegetation fraction composition map as an area of high spatial heterogeneity and dominance of bare soil and rock areas.
- **Unit 6**: The desert fringe batha with a high relative cover of *S. spinosium*, which correlates spatially (mainly in its central extent) to Zone C of dwarf shrub domination.
- **Units 10 and 11**: Cultivated land, which is clearly detected in the cover fraction map. However, their eastern margins exhibit a significant eastwards shift.

In conclusion, it is suggested that the spatial correlation between the two sources may have both ecological and methodological importance. Considering the guiding principles in mapping phytogeographical units, their difference from satellite-driven surface cover combinations is not trivial. Areas of overlap between corresponding units of the two information sources represent the evolution of characteristic landscape patterns and the spatial extension of typical cover proportions comprises only part of the corresponding phytogeographical units, as is the case in the majority of the above-assessed units. This does not necessarily imply an environmental change, since it could originate from differences in mapping principles, as discussed above. Nevertheless, at least one significant environmental change can be inferred: the eastward extension of the cultivated and ecologically disturbed areas. Outside the pine forest plantation plots, the batha and bare soil/rock seem to be the principle components of areas between the typical surface cover composition zones. The dynamic nature of these areas of transition might then be revealed by applying the multivariate unmixing technique on images from intermediate years between the early 1970s and the late 1990s.

10. Summary and conclusions

Wide regional mapping of vegetation formations has ecological (Loveland & Brown, 1999; Reed et al., 1994), hydrological, and climatological (Neilson & Marks, 1994; Running, Loveland, Pierce, Nemani, & Hunt, 1995) importance. In view of changes in habitat conditions at various scales, the task of achieving global, continental, and countrywide coverage from remote sensing is most challenging. This article aimed at contributing to this goal in general, and to the study of Mediterranean vegetation in particular. The climatic gradient between humid and arid conditions extending from the Avisur Highland at the north to Bee‘r Sheva in the south provides a ‘window’ into patterns which vary across zones hundreds of kilometers wide in other parts of the world. Deriving information on physiognomic compositions from a single date image cannot be adequate for the simple reason that the phenomenon under investigation has inherent seasonal variations. A new methodology was presented providing differentiation between physiognomic types at a subpixel level. The methodology is based on the phenomenology of seasonal growth patterns of the different vegetation formations and both temporal and spatial adjustments to the application of the multispectral unmixing technique. Field assessment of physiognomic compositions indicated a high remote sensing retrieval accuracy. New maps of regional vegetation distribution were then produced, allowing analysis of the phytocological structure of the climatic gradient zone. Two significant transition zones were detected, with the northern one representing a distinctive change in primary productivity along the gradient. Utilization of information regarding temporal changes in the location, width, vegetation formations, and plant compositions in these zones is most important for understanding actual and future ecosystem responses to desertification and global warming. Correlation between the spatial extent of phytogeographical units from the maps presented by Danin (1988) and Sapir (1977) and zones of typical surface cover compositions strengthens the ecological information content provided by the application of the multivariate, multispectral unmixing methodology.

This study provides one of the first systematic techniques for the detection of dwarf shrubs which have not gained
significant attention in the remote sensing community despite their worldwide distribution and ecological importance. Dwarf shrub patterns were found to dominate the transition between the bare desert terrain in the south and the shrub dominance in the north with high relative cover at the central part of the gradient. The new data on the extent of dwarf shrubs and their spatial relationship to environmental controlling factors may lead to a better understanding of the dynamics and function of ecosystems in the threshold zones between arid and Mediterranean climates. Furthermore, application of our methodology at a wide regional scale may contribute to the study of the spread of the *S. spinosum* across the Mediterranean in response to agriculture changes, fire, and overgrazing.

Incorporation of physiognomic cover compositional data with radar backscattering from ERS-2 images was found instrumental for determining green biomass (Svoray, Shoshany, Curran, Foody, & Perevolotsky, 2001) and allowed improvement of herbaceous primary productivity mapping along the Avisur Highland–Lehavim climatic gradient (Svoray & Shoshany, in press).

Further improvement of the methodology is needed in order to increase the physiognomic fraction estimation accuracy. Effects due to BRDF (Shoshany, 1993) on the multidate unmixing and better local adjustments of endmember selection are assessed within the second phase of this study which will also incorporate widening of the regional extent of the vegetation mapping.

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