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# The use of remote sensing and GIS for spatio-temporal analysis of the physiological state of a semi-arid forest with respect to drought years

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**Abstract**

Drought years are a very frequent phenomenon in Israel. Between the years 1994/1995 and 2001/2002, Israel experienced four (non-consecutive) years of drought. Consequently the Yatir forest, a pine forest located in the desert fringe, suffered from a notable water shortage. The aim of this research is to detect and assess seasonal/phenological changes and inter-annual changes in the forest trees with respect to the drought effect. The use of a spectral vegetation index, namely the Normalized Difference Vegetation Index (NDVI) to detect stress conditions was implemented by using eight Landsat-TM and ETM+ images. In addition, the change detection NDVI Image Differencing technique was applied for assessing seasonal and inter-annual variations in vegetation. The results indicate similarity between the photosynthetic activity and the NDVI dynamics along the growing season. Considerable NDVI decline was observed between 1995 and 2000 due to the drought events during these years, enabling assessment of the spatial and temporal effects of such a disaster. The NDVI measured from the forest trees was found to be inversely related to the age of the trees due to strong effect of soil background in the younger forest sections that are characterized by lower vegetation density. Topographic attributes such as slope orientation (aspect) were found to affect NDVI only at the year that was not under stress. Under stress conditions, it is evident that environmental factors such as soil type, parent material, and topography are not correlated with NDVI dynamics.


*Keywords:* Remote sensing; Landsat; NDVI; Change detection; Drought; Forest; Semi-arid; Israel

## 1. Background

The recurrence of severe droughts in the Sahel and other regions around the world has led to extensive discussions on the effect of droughts on the life of people and plants, particularly in the arid and semi-

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arid climatologic zones. Forest planting on the desert fringe represents an attempt to combat desertification and rehabilitate of drylands. In Israel, the Yatir forest is such a manmade pine forest situated in the transition between the semi-arid and sub-humid zones (275 mm mean annual rainfall). In order to explore changes and the effects of drought in the forest, the Normalized Difference Vegetation Index (NDVI) was used. The NDVI is the most widely used vegetation index, and it is based on the ratio between the maximum absorption of radiation in the red (R) spectral band versus the maximum reflection of radiation in the near infrared (NIR) spectral band. 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 $\rho$ is the reflectance value in the indicated spectral bands. NDVI values range between $-1.0$ and +1.0 but are usually positive for soil and vegetation. Denser and/or healthier vegetation have higher values. NDVI values of vegetation usually offer an efficient and objective mean for evaluating phenological characteristics (e.g., Justice et al., 1985; Reed et al., 1994; Running et al., 1995) and have long been used to monitor vegetation conditions and changes in vegetation cover (e.g., Lyon et al., 1998; Mass, 1999; Woodcock et al., 2001).

Change detection has become a major application of remotely sensed data because of repetitive coverage at short intervals and consistent image quality (Mass, 1999). Two categories are recognized for the change detection assessment (Yuan et al., 1998). The first is conversion from one land cover type (class) into another and the other is transformations within a given land cover type. The latter can be used for examining the effect of water shortage on the land use of a single renewable natural resource. Several methods for detecting land cover changes were reviewed by Yuan et al. (1998) and Mass (1999). The Vegetation Index Differencing method, and particularly the NDVI Image Differencing, was found to be suitable for the current investigation.

NDVI Image Differencing (ΔNDVI) is a change detection technique that has been used for several applications such as studying the effect of extensive flooding on forest ecosystems (Michener and Houhoulis, 1997), monitoring the impact of urban development (Fung and Siu, 2000), and monitoring the regeneration of Mediterranean shrubland (Svoray et al., 2003). The following equation is applied:

$$\Delta\mathrm{NDVI} = \mathrm{NDVI}_2 - \mathrm{NDVI}_1 \quad (2)$$

where the subscripts 1 and 2 are the NDVI images from dates 1 and 2, respectively. The results of this operation correspond to an increase or decrease in vegetation state or cover. Nelson (1983) showed that using the ΔNDVI technique has stronger relationship to the phenomena of interest in the scene than any single spectral band alone.

The objective of this research is to apply remote sensing and geographic information system (GIS) techniques to monitor changes in the forest on two temporal scales-seasonal and inter-annual changes. The hypothesis is that the NDVI provides a suitable tool to assess changes in the Yatir forest that are related to drought periods due to decrease in vegetation cover and consequent increase of soil background. Spatial data of the forest, coupled into a GIS, can provide a better understanding of the areal changes within the forest during the same hydrological year and patterns of change between the years.

## 2. Material and methods

### 2.1. Study area

The forest area to be studied is located between the Mediterranean and Dead Seas, approximately 31°20′N 35°00′E and 650 m above mean sea level (Fig. 1). This southern part of the mountain chains in Israel is situated between two climate zones: the dry desert with less than 200 mm rainfall per annum and the semi-arid desert that receives between 200 and 300 mm rainfall per annum. In addition to its location on the desert fringe, its relative high elevation plays an important role in defining the climatic characteristics of the forest. The mean annual temperature is about 17.6 °C (ranging between 12.8 and 22.4 °C). The mean winter temperature (November–March) ranges from 9.1 to 12.7 °C, while in summer (June–September) the temperatures range from 23.2 to 24.3 °C.

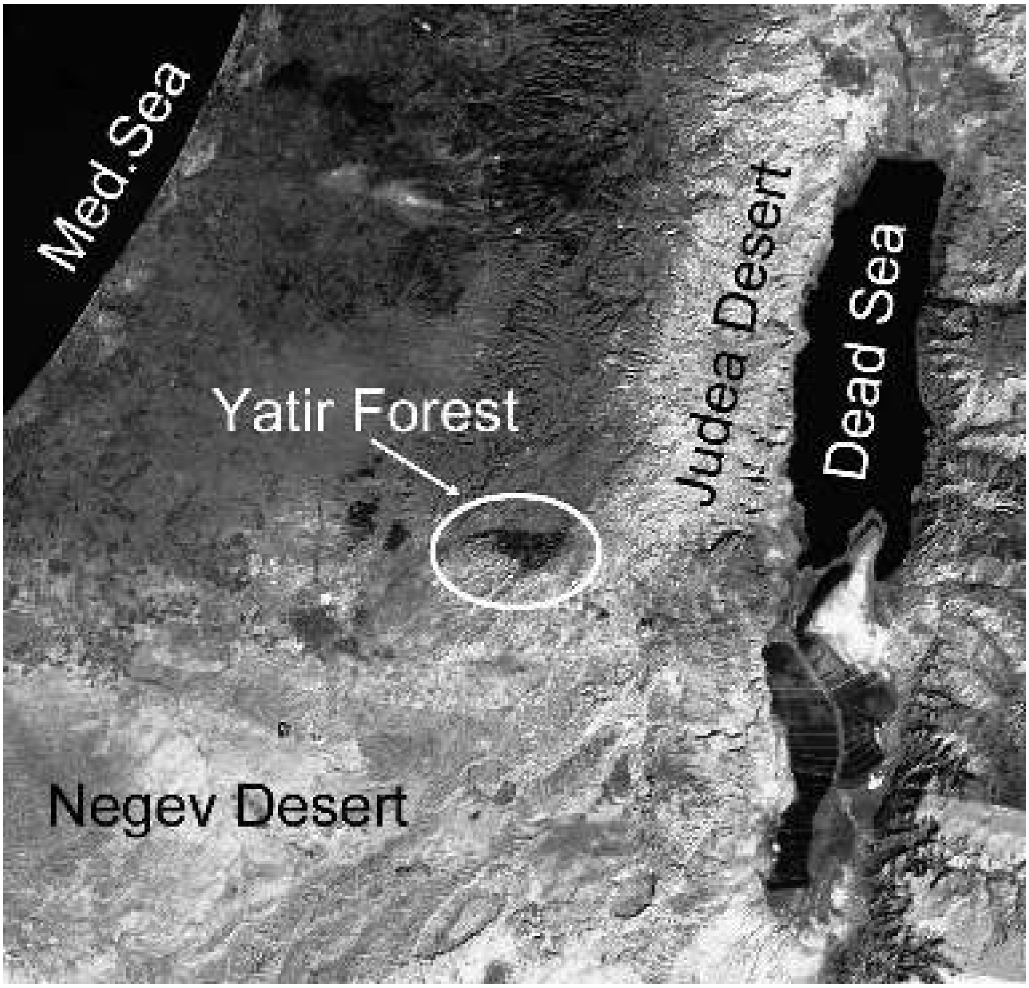


Fig. 1. A Landsat-TM image of central Israel. Note the location of the Yatir forest on the desert fringe, visible as the sharp contrast between bright tones (semi-arid zone) and dark tones (sub-humid zone).

The long-term mean annual rainfall in this region (275 mm) is limited to the winter months (October–April) and characterized by high annual fluctuation, unequal distribution of the events within the rainy season, and above all, its general scarcity. The current research covers a 7-year period (Fig. 2). The hydrological year 1994/1995 is characterized by much more rainfall than the annual mean (360 mm). The next 2 years, 1995/1996 and 1996/1997 were drought years with 158 and 232 mm of rain, respectively. 1997/1998 was an average year with 274 mm of rainfall. The following 2 years, 1998/1999 and 1999/2000 were again drought years with 138 and 157 mm, respectively. Lastly, 2000/2001 was a wet year with 297 mm. In summary, during 5 years (1994/1995–1999/2000 the forest suffered four drought years and one average year. The trees in the forest were planted during four decades: 1960s (28% of the forest); 1970s (38%); 1980s (13.5%); 1990s (20%).

### 2.2. Complementary data

Leaf gas exchange measurements were made in situ with a LI-6400 photosynthesis system (LI-COR) on leaves from portions of the lower canopy exposed to sunlight. Close to ambient conditions were maintained in the leaf cuvette for instantaneous photosynthesis measurements. Photosynthetic response, both to

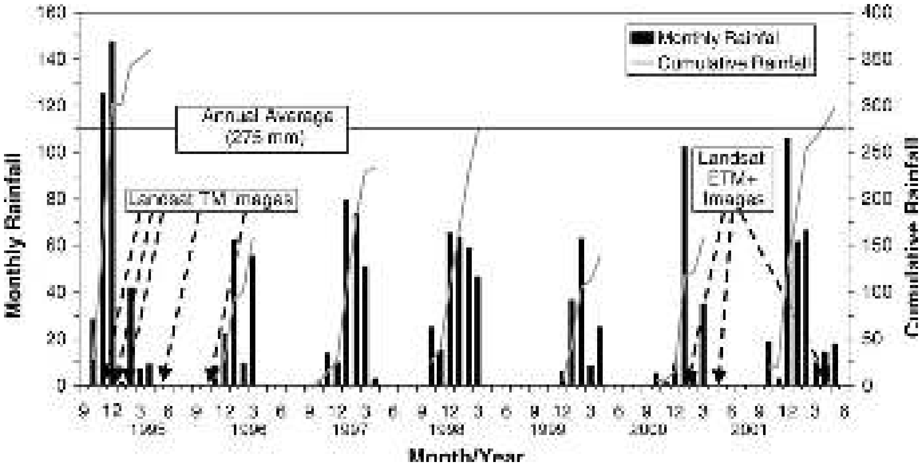


Fig. 2. Yearly distribution of rainfall amounts, cumulative rainfall, and dates of Landsat-TM and ETM+ images that were used in the current study.

irradiance (at growth $CO_2$ concentration of 370 ppm), and to internal $CO_2$ partial pressure (at saturating photosynthetic photon flux density of 1200 μmol $m^{-2}\,s^{-1}$), was established at close to ambient temperatures (16–18 °C) in most days, but 25–27 °C in hot days) and relative humidity (50–60%). All gas exchange parameters were expressed on a projected needle area basis, with the assumption that only illuminated needle surfaces were photosynthetically active (Grünzweig et al., 2003).

### *2.3. Datasets*

Assessment of drought effect was implemented by using eight Landsat-TM and ETM+ images dating from: winter and spring 1994/1995; fall 1995; winter and spring of 2000; and spring 2001. Fig. 2 shows the distribution of Landsat images with respect to monthly and cumulative yearly rainfall.

A second dataset, organized as a GIS, includes spatial information about the following environmental variables: soil type (data provided by the Ministry of Agriculture), geology, plant year (data provided by the Jewish National Fund), slope, and aspect derived by a digital elevation model (DEM).

### *2.4. Image pre-processing*

The aim of the pre-processing operation was to bring all images to the same comparable format. Raw digital numbers of the images were converted to radiance values using the procedure published by Markham and Baker (1986). In order to perform atmospheric correction and to convert the radiance values to surface reflectance values, the Second Simulation of Satellite Signal in the Solar Spectrum (6S) (Vermote et al., 1997) was implemented. For this code aerosols and watervapor contents were acquired from a sunphotometer located at Sede-Boker Campus, about 50 km from the research site. All images were then registered to the New Israeli Grid using 20 ground control points with a root mean square error (RMSE) of less than one pixel. The area of interest (AOI), namely the Yatir forest, was extracted from the geometric corrected images. Finally, a masking of the areas with no trees was performed in order to provide NDVI images with a minimal effect of bare soil and/or annuals that grow in clear-cut plots. Landsat-derived NDVI, for selected dates in winter and spring 1995 and winter and spring 2000 is presented in Fig. 3.

### *2.5. Change detection*

The NDVI Change Detection method (Eq. (2)) was selected for implementing the research goals. Changes within the same hydrological year were computed in order to assess the dynamics of NDVI during the phenological cycle of the trees. In addition, images from the same season in different

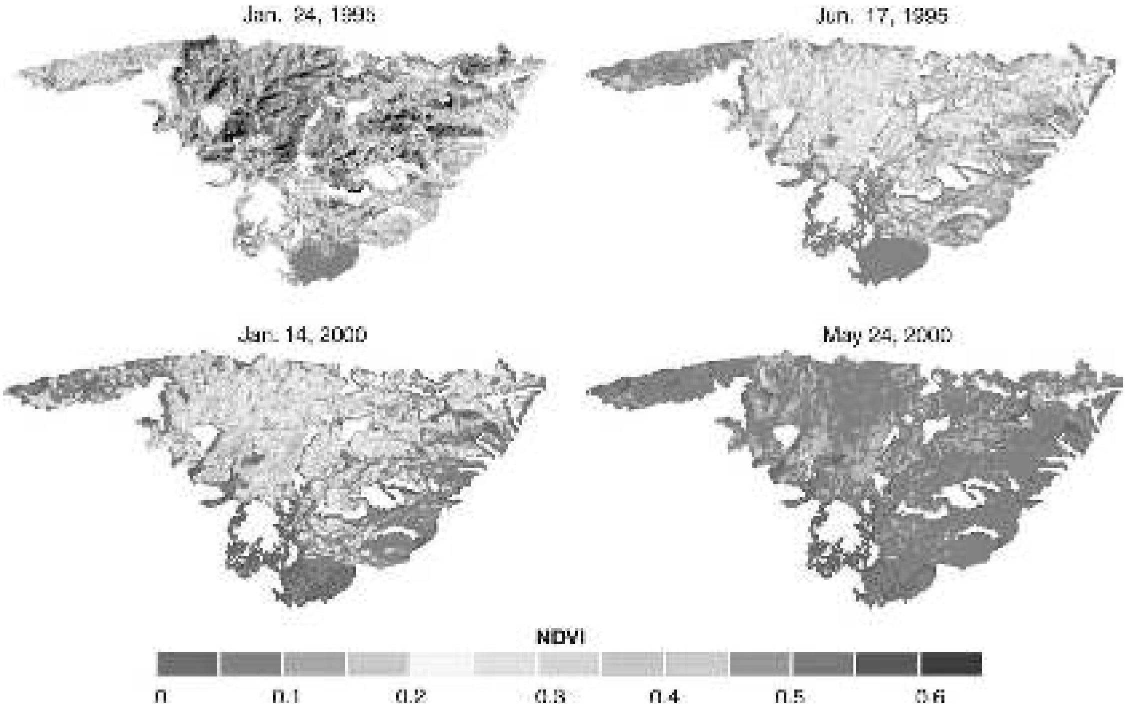


Fig. 3. NDVI images in similar seasons (winter and spring) but for a wet year (1995) and a drought year (2000).

years were computed to characterize the drought effect on vegetation cover due to differing rainfall regimes. Note that the 1994/1995 hydrological year, which represents a wet year with above-mean annual rainfall, occurred after several wet years. Conversely, the 1999/2000 hydrological year represents a drought year, the fourth drought year in a 5-year period.

A common way to assess changes is based on determination of thresholds in terms of standard deviation levels from the mean ΔNDVI ($\overline{\Delta\text{NDVI}}$) (Fig. 4A). In this manner, one can distinguish between changed and unchanged pixels as well as between negative and positive changes (Jensen, 1986). In the current study, in the cases in which the entire forest changed in only one direction, the threshold is determined in the minimal NDVI value (≈0) and not in adjacency to the mean in order not to lose meaningful information (Fig. 4B). Steps of 1 standard deviation (S.D.) from the ($\overline{\Delta\text{NDVI}}$) determined the magnitude of the change in both case studies described above.

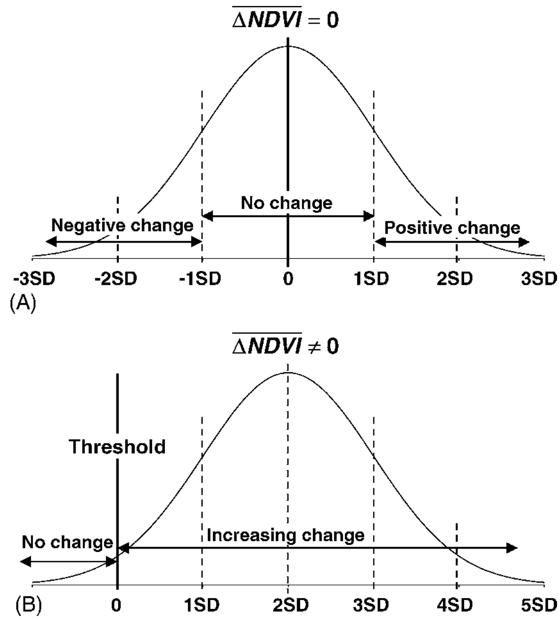


Fig. 4. Schematic illustration of two change detection approaches used in the study.

## 3. Results and discussion

### 3.1. Seasonal dynamics of NDVI

In order to better understand the dynamics of the NDVI values along the year, one should consider the physiology of Pine (Pinus) trees in Israel. The origin of the pine trees is northern Europe where they are productive during summer when temperatures rise above 0 °C while throughout the winter they turn into a dormant mode (Raven et al., 1999). In Israel, pine trees respond differently to the sub-humid climatic conditions. Fig. 5 illustrates the dynamics of photosynthetic activity from September 2000 to October 2001. Assuming that this trend does not change between the years (except the magnitude of the activity) it is possible to relate the 1994/1995 images to this graph as illustrated by the mean and standard deviation of NDVI values extracted along a transect across the forest from the five Landsat images of 1994/1995 (Fig. 5). It can be seen that relatively high NDVI values exist during the rainy season (December and January) similar to the high photosynthetic activity stemming from the relatively high temperature of the Mediterranean climatic zone. It is important to note that like the pines in Europe, these trees in Israel do not grow new needles in winter although the conditions are sufficient. This is because the phenotype of the pine changes over time but not the genotype, which means that pine trees in Israel change their response to the environment and conduct photosynthesis during the winter months. However, the ability to create and grow new needles has not changed and like pines in northern countries this happens during spring and summer. The image of October 1995 is characterized by higher NDVI values than exist during the summer even before the winter rains began. The reason is that temperature is also a limiting factor. In this region temperatures can be as high as 32 °C during the summer, decreasing around mid-September and enabling increasing rates of photosynthetic activity.

### 3.2. Inter-annual dynamics of NDVI

Fig. 6 represents the NDVI transects across the forest (8.5 km) during the rainy year in 1994/1995 (360 mm) and the drought year 1999/2000 (130 mm of rain after three non-consecutive years of drought). The curve of January 1995 shows the highest values of NDVI that are related to the photosynthetic activity of a healthy forest. The curve of June 1995 shows lower NDVI values, as expected due to closing of the stomata during the late spring and summer. Looking at the same months 5 years later reveals the effect of water shortage on the NDVI due to 4 years of drought. The January 2000 curve has higher NDVI values than May of the same year, however compared to January 1995 these values are significantly lower. Note that the

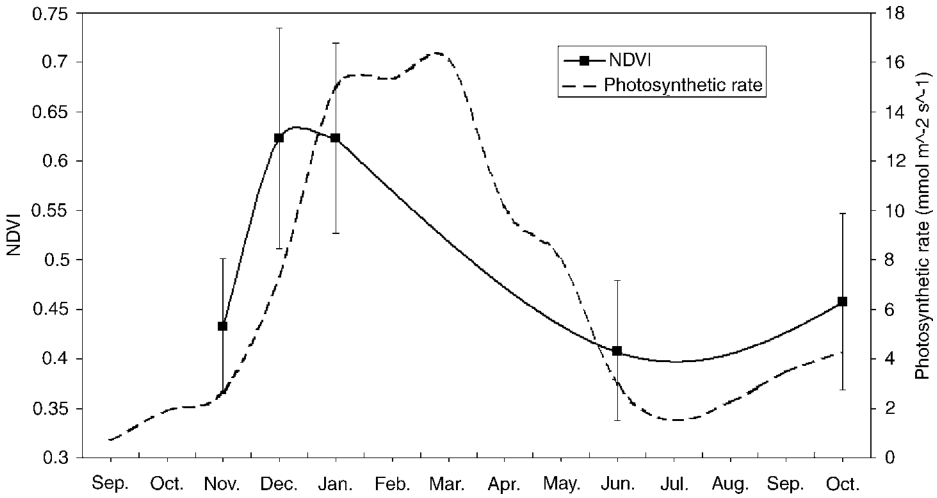


Fig. 5. Annual dynamics of the photosynthetic fluxes of the Yatir forest for the year 2000/2001 (mmol $m^{-2}$ $s^{-1}$) in comparison to the annual dynamics of NDVI for the year 1994/1995.

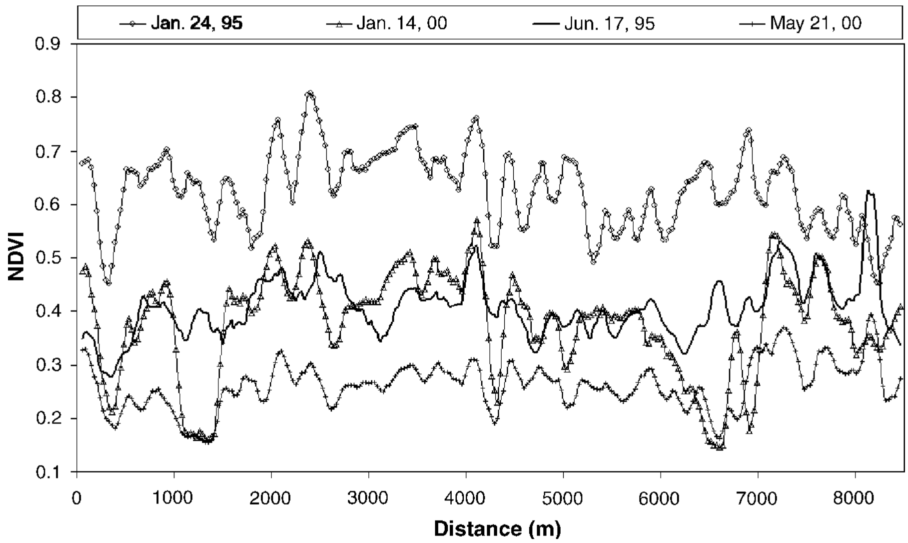


Fig. 6. NDVI values across the forest (west–east transect) for winter and spring of 1995 and 2000.

NDVI values of January 2000 almost perfectly match the ones of June 1995. Also note that the effect of rainfall amounts, after 4 years of drought, is less profound than the effect of rainfall on the forest during a rainy year. The amount of rain required to recover the trees into the growing mode needs to be greater than the amount of rain needed in 1994/1995.

### 3.3. ΔNDVI images

Numerous change detection products were computed in order to observe the magnitude of the change along the phenological cycle of different years and in the same season but between years. According to the previous discussion, a threshold value was derived from the image as one standard deviation (S.D.) from the ΔNDVI mean in cases where the mean was between −0.1 and +0.1. Otherwise, when the mean was either smaller −0.1 or greater than +0.1, ΔNDVI was set to 0 as the reference point. Table 1 summarizes the mean and S.D. of the nine case studies. Positive mean indicates recovery of the forest while negative mean indicates degradation.

Fig. 7 presents the ΔNDVI images for the seasonal case studies along with the respective frequency histograms of the change categories. Each category represents one standard deviation step. The difference image computed from November to December 1994

Table 1
Pairs of images used for the change detection analysis along with the change statistics – mean and standard deviation (STDV)

| Change period | | Comments | ΔNDVI | |
|---|---|---|---|---|
| Image 1 | Image 2 | | Mean | STDV |
| November 21, 1994 | December 7, 1994 | Monitoring phenology, same season | 0.203 | 0.107 |
| December 7, 1994 | January 24, 1995 | Monitoring phenology, same season | 0.0018 | 0.114 |
| January 24, 1995 | June 17, 1995 | Monitoring phenology, different seasons, same (wet) year | −0.232 | 0.106 |
| June 17, 1995 | October 7, 1995 | Monitoring phenology, different seasons, same (wet) year | 0.045 | 0.06 |
| January 14, 2000 | May 21, 2000 | Monitoring phenology, different seasons, same (drought) year | −0.247 | 0.11 |
| January 24, 1995 | January 14, 2000 | Inter-annual change, same (winter) season | −0.1 | 0.091 |
| June 17, 1995 | May 21, 2000 | Inter-annual change, same (spring) season | −0.116 | 0.057 |
| June 17, 1995 | May 24, 2001 | Inter-annual change, same (spring) season | −0.112 | 0.062 |
| May 21, 2000 | May 24, 2001 | Inter-annual change, same (spring) season | 0.004 | 0.038 |

Positive mean indicates recovery of the forest while negative mean indicates degradation.

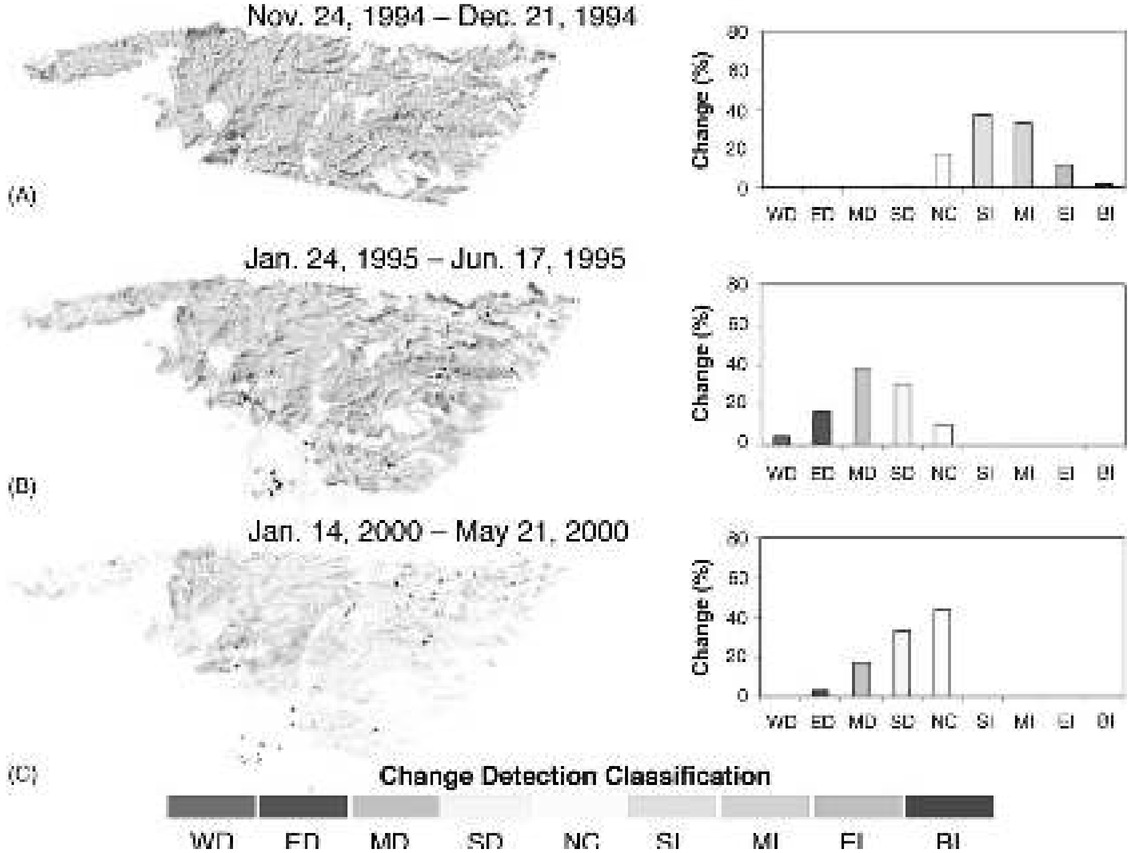


Fig. 7. NDVI Image Differencing products for the images of phonological analysis along with the respective frequency histograms of the change categories. Each category represents one step of standard deviation. (A) November 21, 1994–December 7, 1994; (B) January 24, 1995–June 17, 1995; (C) June 17, 1995–October 7, 1995. Note the matching of colors between the images and the histograms.

emphasizes the rainfall effect on the forest at the beginning of the winter (Table 1, Fig. 7A). The same trend continues between December 1994 and January 1995 (Table 1). On the other hand, decrease in NDVI values is observed in the image computed from January to June 1995 (Table 1, Fig. 7B) as a response to lower photosynthetic activity as shown in Fig. 5. The positive change between June and October 1995 due to the decrease of temperature has already been discussed. Note that increase of NDVI due to decrease in temperature is lower than the response of increasing NDVI with higher rainfall values. This is supported by the findings of Schultz and Halpert (1993) who concluded their research with the statement that in warm regions temperature generally plays a marginal role in increasing the NDVI compared to rainfall or water shortage. The seasonal change between January and May 2000 (Table 1, Fig. 7C) indicates a similar change as in 1995 but less dramatic since the forest was already relatively dry in January due to the drought (Fig. 6).

Inter-annual changes are illustrated in Fig. 8. The biggest negative change is observed between January 1995 and January 2000 due to the droughts in-between the 2 years (Fig. 8A, Table 1). The change between June 1995 and May 2000 was less pronounced since both images represent the season with less photosynthetic activity (Fig. 8B, Table 1). The moderate recovery of the forest as a result of a new wet year expressed as positive change, is demonstrated in Fig. 8C and Table 1. Note however that most of the pixels remain unchanged.

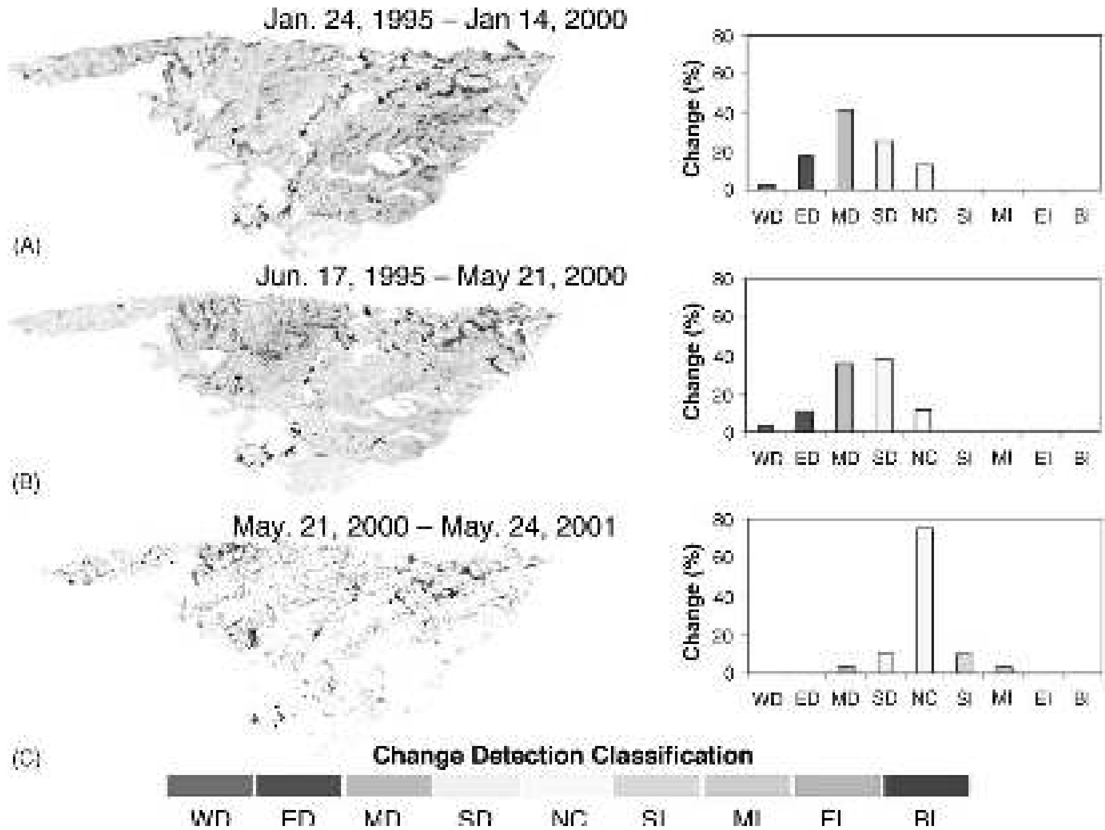


Fig. 8. NDVI Image Differencing products for selected images of inter-annual analysis along the phonological cycle along with the respective frequency histograms of the change categories. Each category represents one step of standard deviation. (A) January 24, 1995–January 14, 2000; (B) June 17, 1995–May 21, 2000; (C) May 21, 2000–May 24, 2001. Note the matching of colors between the images and the histograms.

### 3.4. The effect of environmental variables on NDVI and ΔNDVI

The effect of environmental variables (plant year; topographic aspect and slope; soil type; geological formation) on NDVI and ΔNDVI was studied for the five dates of acquisition. To assess the relationship between these environmental variables and the vegetation status and change, three statistical tests were performed: (1) analysis of variance (ANOVA) to assess the effect of each environmental variable on NDVI and ΔNDVI separately; (2) multivariate analysis of variance (MANOVA) to assess the effect of combinations of environmental variables on NDVI ΔNDVI frequencies; (3) Student's *t*-test to test trends of NDVI and ΔNDVI frequencies within environmental variables that were found to have an influence.

Table 2
ANOVA between NDVI and the different environmental variables, bold numbers indicates high Pv

| | January 24, 1995 | June 17, 1995 | January 14, 2000 | May 21, 2000 | May 24, 2001 |
|---|---|---|---|---|---|
| Plant year | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** | **<0.0001** |
| Aspect | **0.0002** | 0.5896 | 0.5055 | 0.4522 | 0.1847 |
| Slope | **0.0122** | 0.5368 | 0.5382 | 0.1457 | 0.0621 |
| Soil | **0.0006** | 0.4049 | **0.0224** | 0.4935 | **<0.0001** |
| Geology | 0.1259 | 0.3378 | 0.1547 | 0.051 | 0.1166 |

Table 3
ANOVA between ANDVI and the different environmental variables, bold numbers indicates high Pv

| | | | | | |
|---|---|---|---|---|---|
| Image 1 | January 24, 1995 | January 14, 2000 | January 24, 1995 | June 17, 1995 | May 21, 2000 |
| Image 2 | June 17, 1995 | May 21, 2000 | January 14, 2000 | May 21, 2000 | May 21, 2001 |
| Plant year | **0.0003** | <**0.0001** | **0.0387** | 0.9332 | **0.016** |
| Aspect | **0.0002** | 0.8082 | **0.0104** | 0.9937 | <**0.0001** |
| Slope | 0.1854 | 0.2032 | 0.6546 | 0.9981 | <**0.0001** |
| Soil | 0.3673 | 0.0688 | 0.131 | 0.9999 | <**0.0001** |
| Geology | 0.4305 | 0.1066 | 0.392 | 0.9955 | <**0.0001** |

Table 4
MANOVA between NDVI and combinations of plant year and other environmental variables, bold numbers indicates high Pv

| | January 24, 1995 | June 17, 1995 | January 14, 2000 | May 21, 2000 | May 24, 2001 |
|---|---|---|---|---|---|
| Plant year × aspect | **0.0412** | 0.7221 | 0.5365 | 0.434 | **0.0296** |
| Plant year × slope | 0.2446 | 0.7366 | 0.9374 | 0.7189 | 0.8305 |
| Plant year × soil | **0.0501** | 0.4479 | **0.0003** | <**0.0001** | <**0.0001** |
| Plant year × geology | 0.774 | 0.3406 | 0.3082 | **0.0362** | 0.12 |

The ANOVA results under conditions of different environmental conditions are presented in Table 2. One can see that plant year has the highest probability of variance (Pv) among all NDVI images. Another important result is seen in the January 1995 image where high Pv is presented in four out of five environmental variables. Table 3 shows ANOVA test results under different environmental variables. In this analysis plant year shows again the highest Pv.

Although generally only plant year showed high Pv, the idea of MANOVA test was to examine the possibility of an integrated effect of two variables on the NDVI and ΔNDVI that might be stronger than the effect of a single variable. Table 4 shows the summary of the MANOVA test that produces significant results. The combination of two variables – plant year and soil – reveals the highest Pv among all cases (except in the spring 1995). The 1995 image represents the forest status after several rainy years. Apparently, under these conditions, the aspect and slope affect the reflectance from the forest and thus also the NDVI values. In contrast, under drought conditions, the environmental variables do not affect the NDVI distribution since all the forest is already under stress.

The last step aimed to examine the trend of changes in NDVI and ΔNDVI at different plant year groups (separately) using the Student's *t*-test analysis. Mean NDVI values measured from trees with a similar plant year were computed. Tables 5 and 6 show the *t*-test results for plant year variable between the NDVI and ΔNDVI values, respectively. In all cases trees that were planted in the 1960s reveal high NDVI values and high negative change values, while trees that were planted in the 1990s reveal low NDVI values and low negative change values. This means that there is a distinct difference between the NDVI and ΔNDVI

Table 5
NDVI plant year *t*-test results where of variance (Pv) and probability of mean (Pm) are shown in two categories

| | 60–70 | | 60–80 | | 60–90 | | 70–80 | | 70–90 | | 80–90 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv |
| January 24, 1995 | *** | *** | NA | | NA | *** | *** | *** | *** | *** | NA | *** |
| June 17, 1995 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** |
| January 14, 2000 | *** | *** | *** | *** | *** | *** | *** | NA | *** | * | *** | NA |
| May 21, 2000 | *** | *** | * | *** | NA | *** | NA | *** | NA | *** | NA | |
| May 24, 2001 | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | *** | NA |

[*] Pm < 0.05.
[***] Pm < 0.001.

Table 6
ΔNDVI plant year *t*-test results where of variance (Pv) and probability of mean (Pm) are shown in three categories

| | | 60–70 | | 60–80 | | 60–90 | | 70–80 | | 70–90 | | 80–90 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv | Pm | Pv |
| January 24, 1995 | June 17, 1995 | ** | *** | *** | ** | *** | *** | *** | *** | *** | ** | *** | *** |
| January 14, 2000 | May 21, 2000 | ** | *** | *** | *** | *** | *** | *** | *** | *** | *** | ** | * |
| January 24, 1995 | January 14, 2000 | *** | *** | *** | NS | *** | NS | *** | *** | *** | *** | *** | NS |
| June 17, 1995 | May 21, 2000 | *** | *** | *** | *** | *** | *** | NS | *** | *** | *** | *** | *** |
| May 21, 2000 | May 24, 2001 | NS | *** | *** | *** | *** | *** | *** | *** | *** | *** | NS | NS |

* Pm < 0.05.
** Pm < 0.01.
*** Pm < 0.001.

groups of trees planted in different years. The suggested explanation is as follows: trees planted in the 1990s are mostly broad leaf trees (*Pistacia*, *Quercus*, and *Ceratonia*) while trees planted from the 1960s to 1980s are pine trees. Broad leafs are planted at an 8 m distance from one another while the pine trees are planted with gaps of 2 m. The plants were 30 cm tall when planted (Abu-Kylaan (KKL), personal communication) and therefore much of the reflectance received is from the soil background among the trees. Table 2 confirms these results where one can notice that plant year is the only variable affecting the distribution of NDVI in the forest in all cases. Since NDVI values in the trees planted during the 1990s are primarily low, the water shortage, that mostly affects needles, has more impact on fully grown trees with extensive needle cover than on first-year needle trees (when they grow mostly vertically). Tables 3 and 6 confirm this conclusion.

## 4. Conclusions

The aim of this study was to monitor temporal changes in NDVI values in the Yatir forest drought conditions and spatial variation in environmental conditions. Despite limitations caused by the effect of differences in bare soil reflectance and a relatively low number of images, six conclusions can be drawn from this research:

1. Changes of in NDVI values during the growing season show that changes in forest physiology could be detected due to changes in photosynthetic activity. During the winter, high photosynthetic activity values are detected due to the relatively low temperature (in comparison with summer temperatures) and the high water availability. Conversely, during the summer, stomata close and photosynthetic activity decreases as a result of high temperature and absence of water. All those variables affect the state of the forest greenness and are reflected in the NDVI fluctuations along the year. This result shows the changes in phenotype in Pines trees with their immigration from Europe to Israel: a change from high photosynthetic activity in the summer months in Europe to high photosynthetic activity in the Israeli winter.
2. Annual comparisons show large changes in the NDVI values. Drought years seriously affect the amount of water available for the trees, and as a result of water shortage, the trees in Yatir forest show stress during drought years. This effect is well-demonstrated by the decrease in NDVI values between the winter and spring of 1995 and winter and spring of 2000.
3. In all cases tested in this research, plant year was the most significant factor influencing the spatial distribution pattern of NDVI in the forest and the values of change in the NDVI images. Trees planted in the 1990s are most likely to be less affected by drought and water shortage during the hydrological year and between years.
4. The insignificant correlation between NDVI, ΔNDVI, and the other environmental variables: soil, geological formations, and topographic slope imply that these measures are more sensitive to changes in the plant/seedling size than to change due to indirect effects from environmental variables.
5. Slope orientation (aspect) does explain the variance in NDVI values when the forest is in its prime condition (high water availability and moderate

temperature). The assumption that north-facing slopes cause more intensive photosynthetic activity and thus highest NDVI values at all times does not apply to Yatir (as a case study for desert forest) where water shortage affects the entire forest without a dependency on slope orientation.

6. According to the data, plant year (i.e., trees age) and soil type have a strong integrated effect on NDVI and thus on forest state. The effect was found considerably strong in drought years. In contrast, all other combinations of environmental variables (slope, aspect and decline, and geological formations) and plant year show weak effect on the NDVI.

In summary, NDVI image differencing has proven to be a useful and accurate method for tracing physiological changes in the Yatir forest, which serves as a case study for a manmade forest in the desert fringe.

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