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Application of NOAA AVHRR for monitoring vegetation conditions and biomass in Jordan

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Monitoring vegetation of arid and semi-arid zones by remote sensing can help natural resource management. Techniques previously used in Africa are applied to monitor vegetation conditions and productivity in Jordan. The historical normalized difference vegetation index (NDVI) data were extracted from the FAO ARTEMIS and NASA PAL archives, and processed to stratify the major vegetation zones of Jordan. Statistical distribution of the NDVI for each 10-day period of the year was extracted for each vegetation zone, and quartile probability ranges were used to define four classes of vegetation condition, represented as vegetation productivity indicators (VPI). Images of NOAA LAC were acquired from the local receiving station at the Meteorological Department of Jordan and processed in real time to produce VPI maps that detected the temporal variations in vegetation condition in different parts of the country. In the second part of the research, vegetation productivity of grazing reserves was correlated against the NDVI derived from LAC images. A significant correlation was found between the above-ground biomass of shrubs and the NDVI derived from NOAA LAC images. The study clearly showed the suitability of NOAA AVHRR data for monitoring vegetation conditions and productivity in Jordan.

Keywords: remote sensing; NOAA AVHRR; NDVI; Jordan; arid zone; vegetation; rangeland

Introduction

Rangeland management requires an efficient system to monitor its vegetation, because vegetation is the source of rangeland forage and has an important role in protecting soil from erosion by water and wind (Backhaus *et al.*, 1989; Ray, 1995). This research forms part of the Jordan arid zone productivity project (JAZPP). The project is concerned with sustainable development in the zone with 100–200 mm mean annual rainfall (Fig. 1), which covers more than 13% of the total area of Jordan. The JAZPP impact zone is a transitional zone of Jordan's Badia, which receives less than 200 mm mean annual rainfall. This area covers approximately 90% of the total area of the country, and is classified as rangeland (Juneidi & Abu-Zanat, 1993).

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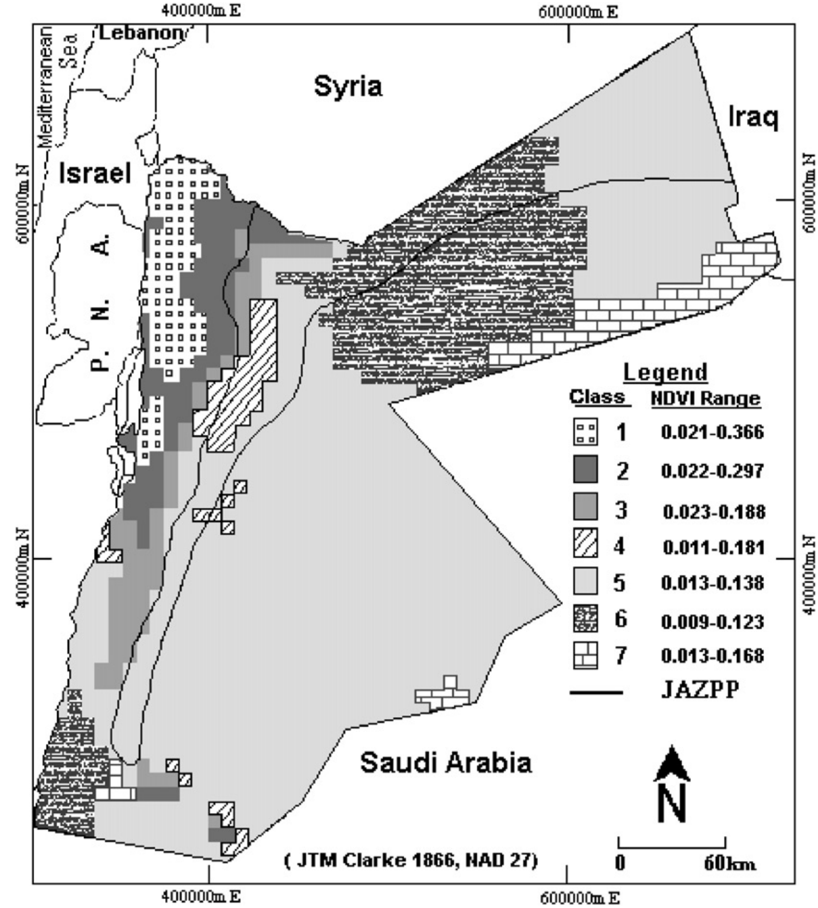

Figure 1. Major NDVI-response classes of Jordan, derived from the cluster analysis of 15-year-averaged dekadal NDVI images calculated from the ARTEMIS and PAL archives.

Previous research (Al-Hadidi, 1996), using climatic data, showed that the transition zone suffered from high risk of desertification and is expected to lose its productivity over time. Overgrazing, cultivation and periodic droughts are the major causes of rangeland degradation in this zone (Juneidi & Abu-Zanat, 1993). Thus, the aim of the JAZPP is to develop the region through sound land use recommendations and technology transfer to farmers. One major land use recommendation proposed by the JAZPP is to develop improved rangeland. This can be facilitated by a monitoring system that can provide information about vegetation condition and productivity. This research aims to develop a practical and inexpensive vegetation monitoring system for the whole country (89,500 km^2), including the impact zone of JAZPP.

The presence of vegetation in the arid and semi-arid zones of Jordan is highly variable through time and space depending on actual rainfall. The green flush lasts for a very short time and tends to be overgrazed shortly after it occurs. Thus, for monitoring the vegetation of these zones high temporal frequency data is required. Satellite imagery data of the NOAA AVHRR can be used for this purpose. The advantages of using the AVHRR data for monitoring vegetation are: the frequent coverage, the good calibration, the low price and the direct reception with a low cost ground station (Cracknell, 1997).

Previous studies (Hutchinson, 1991; Lambin *et al.*, 1993) have shown the advantage of using AVHRR data for monitoring vegetation condition compared to other methods that interpret rainfall measurements. In Jordan, the use of rainfall data to monitor vegetation is not possible because of the scarcity of rainfall measurements in the Badia, and the poor spatial correlation between rain gauges. As an alternative, remote sensing data of NOAA AVHRR combined with ground data is used in this study as the major tool for monitoring vegetation conditions and productivity in Jordan.

Since the early 1980s data from NOAA AVHRR have been used extensively to monitor and to study dryland vegetation (Millington *et al.*, 1994). Previous studies (Tucker *et al.*, 1985,1986; Prince & Tucker, 1986; Kennedy, 1989; Belward, 1991; Prince, 1991; Maselli *et al.*, 1992; Garcia, 1993; Groten, 1993; Fuller, 1998; Sannier *et al.*, 1998*b*) have shown the usefulness of the NOAA-AVHRR-normalized difference vegetation index (NDVI) for monitoring vegetation at different scales. Tappan *et al.* (1992) found that the NDVI image data were a useful tool for monitoring growing conditions of rangeland and for making long-term productivity comparisons between the different rangeland types. Furthermore, Mout *et al.* (1997) used the NDVI as an indicator of desertification since it related to vegetation greenness.

The archived NDVI images are an invaluable source of information that can contribute to vegetation and land degradation studies. Among the NDVI archives are the African real time environmental monitoring information system (ARTEMIS) and the NASA pathfinder AVHRR land (PAL) archives. These archives (7·6 km-resolution) contain composites of the maximum NDVI value recorded for each dekad (10-day interval) as described by Holben (1986).

In order to assess vegetation condition, current NDVI can be compared with historical NDVI data to assess severity of departures from normal conditions. Previous studies (Hutchinson, 1991, Lambin *et al.*, 1993) compared current NDVI images to previous dekads and the mean image. In another study, Kogan (1990) used the vegetation condition index (VCI) to monitor vegetation condition. The index was computed by comparing the NDVI value of each image pixel to that pixel's maximum and minimum value at the same time point in all years spanned by the series.

The above studies assumed that either the NDVI is normally distributed, or its range represents all the possible variations with the same frequency and probability. In many cases, particularly in arid zones where vegetation is sparse, these assumptions are unrealistic. As an alternative, the present work used the vegetation productivity indicator (VPI) proposed by Sannier *et al.* (1998*b*) to monitor vegetation conditions in Jordan. The method, described below, produces VPI maps by assessing the severity of departures from normal, taking into consideration the actual statistical distribution and the probability of having a smaller NDVI.

While VPI maps enable rangeland conditions to be qualitatively assessed in relation to previous seasons, estimates of the actual productivity are needed to assist rangeland management and estimation of carrying capacity. One option to estimate rangeland productivity is by field sampling. However, for large areas, this option is not feasible because of the high number of samples required and logistical difficulties of carrying out field work. Alternatively, remote sensing data can be used to obtain estimates of vegetation productivity rapidly and nondestructively at relatively low cost, compared to field survey methods. The spatial extent and frequency of coverage of the NOAA AVHRR made it a feasible option for estimating vegetation productivity for large areas.

Previous research on the African Sahel (Tucker *et al.*, 1985; Prince & Tucker, 1986; Taylor *et al.*, 1986; Hiederer & Wyatt, 1990; Prince, 1991; Groten, 1993; Fuller, 1998; Sannier *et al.*, 1998*b*), showed good correlations between the NDVI derived from NOAA AVHRR data and vegetation productivity. Similar findings (Kennedy, 1989) were observed in the Mediterranean region of Tunisia, where the NDVI was highly correlated with the above-ground biomass and percentage cover of different shrub species.

Although this area of research is still under investigation in Jordan, it is highly relevant to rangeland management and necessary in order to estimate the productivity levels for different parts of the country including the impact zone of JAZPP. The estimation of vegetation biomass at the scale of the AVHRR, however, requires availability of the imagery at the time of sampling, selection of suitable sampling sites and appropriate design for field sampling procedures (Hiederer & Wyatt, 1990).

A previous trial (Marrianne *et al.*, 1996) in the Badia showed no obvious relationship between the NDVI derived from NOAA AVHRR and percentage vegetation cover. The weak correlation was attributed to the very low densities of vegetation in the open range and other factors across the selected study sites. The second aim of this work was to see if an alternative methodology could be successful in obtaining a workable correlation.

Monitoring vegetation conditions in Jordan

Vegetation conditions can be studied at the pixel level (1 km) using the NDVI derived directly from NOAA AVHRR imagery. However, this requires the calculation of NDVI statistical distribution at the 1 km-spatial resolution from a time series of data that is not yet available. In this research, time-series data from the ARTEMIS and PAL archives (spatial resolution of 7·6 km) was used to estimate the statistical distribution of NDVI.

The time-series data comprised images for 15 years during the period from 1981 to 1997. The images were composites of the maximum NDVI value recorded for each dekad as described by Holben (1986) and were subsets of either the ARTEMIS or the NASA PAL imagery. Data from both archives were corrected following the procedure described by Sannier *et al.* (1998*a*) to compensate for differences in the processing chains. NDVI values for cloudy pixels were interpolated using the method suggested by Groten (1993).

The VPI method requires the local statistical distribution of the NDVI to be estimated. This could be done on a pixel-by-pixel basis, but a simplified approach was to stratify the country into zones having similar NDVI response patterns. This was done by cluster analysis on images consisting of the temporal mean NDVI values produced for each of the 36 dekads of the year. It was not possible to carry out cluster analysis using all the 36 mean NDVI images because of software limitations. Therefore, principal component analysis (PCA) was carried out using the 36 images to reduce the number of dimensions. The first three principal components, which accounted for 95·7% of the total variance in the 36 images, were produced and then classified by clustering with the ISODATA algorithm (PCI, 1997).

The first classification attempt showed only three distinctive classes with one main class covering about 80% of the country. Similar results of classifications, using the NOAA GAC data, have been reported for the Near East region which includes Jordan (Kouchoukos *et al.*, 1998; Smith *et al.*, 1999). However, visual inspection of the imagery indicated the likely presence of more classes representing subtle variations of vegetation within the Badia. Thus, clustering was performed again for the NDVI data within each of the three classes. This hierarchical technique increased the sensitivity of the classification procedure.

Results from this stage (Fig. 1) showed seven distinctive NDVI-response classes representing the different zones in Jordan. The classes were assessed visually by inspecting the NDVI profiles extracted from the signatures' means as shown in Fig. 2. These profiles showed the relative vegetation dynamics for each class. Visual

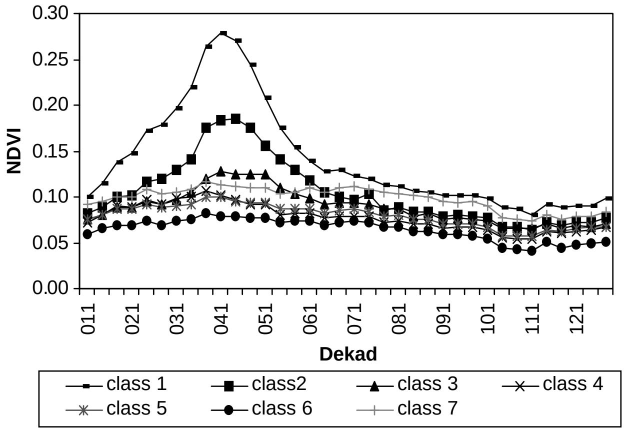

Figure 2. Temporal-average NDVI profiles (1981–1997) for the major NDVI-response classes.

comparison of the classification produced from cluster analysis was made with available maps: of vegetation (Zohary, 1973), of rangeland classification (HTS, 1956) and of land cover (MOA, 1995). Classes 1 and 2 cover a small area in the north-west of Jordan and extend through the mountain range that has mean annual rainfall of over 200 mm. In addition, these classes include the irrigated area in the Jordan Valley. The temporal-mean NDVI profiles (in Fig. 2) showed that both classes were characterized by relatively higher NDVI values and a longer growing season than other classes. According to Zohary (1973), part of the area covered by class 1 supports the best vegetation in the country, particularly the forest climax of *Pinus halepensis, Quercus calliprinus* and *Pistacia* spp. The area under these two classes, however, is characterized by rapid urban development which may result in a reduction of the cropped area and the restriction of further agricultural development of the area in the future. Classes 3 and 4 cover the western part of JAZPP where barley is cultivated. The natural vegetation under these classes is mainly composed of small shrubs and bushes including *Retama reatum, Ziziphus lotus, Artemisia herba alba. Noea mucronata,* and *Anabasis syriaca*. According to the classification, parts of classes 2–4 exist in the southern part of the country near Al-Disi where irrigation farming takes place. This results in relatively higher NDVI values for these areas compared with the surrounding desert. Class 5 represents the area of desert pavement that constitutes about 60% of the country. Class 6 is dominated by basalt rock, while class 7 represents the driest area of the country, and is covered by sheets of sand. Classes 5–7 cover the majority of Jordan and are characterized by very poor, sometimes non-existent, vegetation. Vegetation of the above classes is restricted to the wadis (valleys) where enough moisture is available. The natural vegetation in these classes is *Artemisia* spp., *Achillea fragrantissima, Phlomis, Astragalus, Stipa* and *Trigonella* spp.

Time-series analysis for the vegetation classes (Fig. 2) showed variations in the NDVI with respect to time for the different classes. Distinctive growth peaks characterized classes 1–3. Classes in the arid zone (especially classes 6 and 7) were characterized by flat NDVI curves showing little or no vegetation growth. Class 6, dominated by basalt rock, was characterized by the lowest NDVI values throughout the year. The vegetation in class 6 is restricted to limited areas between basalt gravel areas called 'marabs' (out-wash plains). Finally, class 7 showed a flat curve similar to that of class 6, but with relatively higher NDVI values. This is attributed to the high reflectance of the sand sheets in both channels of NOAA AVHRR and resulted in relatively high NDVI values throughout the year.

Table 1. *Description of VPI classes in relation to probability of having a smaller NDVI*

VPI class	Probability level
Very low	$p<0{\cdot}25$
Low	$0{\cdot}25<p<0{\cdot}5$
Average	$0{\cdot}5<p<0{\cdot}75$
High	$p>0{\cdot}75$

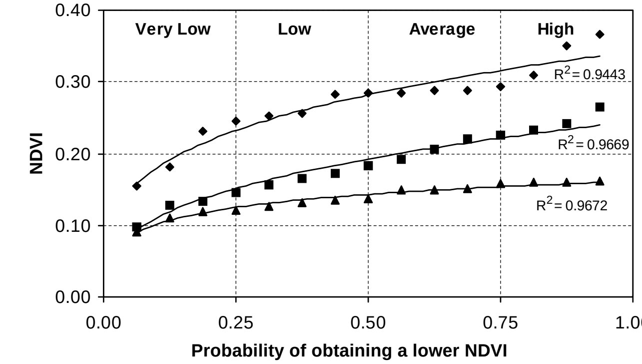

Figure 3. Probability of a lower NDVI and VPI class limits in the second dekad of April for classes 1–3.

The VPI methodology proposed by Sannier *et al.* (1998*b*) assesses the occurrence of extreme vegetation conditions using methods usually used for assessing the probability of extreme hydrological events, as described by Linsley *et al.* (1988). NDVI values extracted from the historical data were ranked in ascending order and the probability (p) of having NDVI less or equal to a given value was estimated by applying the formula defined by Weibull (1939) as follows

$$p = m/(n+1)$$

where m is the rank and n is the number of years.

The probability was plotted against the corresponding NDVI values for each dekad and for each class. A simple least-squares fit was used to interpolate estimates of the NDVI for specified probabilities. Quartile ranges of the probability of having a smaller NDVI for each vegetation condition class and for each dekad were calculated, and defined the VPIs as indicated in Table 1. Selection of the VPI categories (very low, low, average and high) was made with reference to previous research concerned with the assessment of vegetation condition (Humphrey, 1949) and land degradation (FAO/UNEP, 1984).

An example of the probability plot for the second dekad of April for classes 1–3 is shown in Fig. 3. It can be seen that for the same NDVI value, the probability of a smaller NDVI will differ depending on the class. For instance, an NDVI value of 0·20 corresponds to a very low VPI for class 1, average for class 2 and high for class 3. Thus the advantage of the VPI is that it designates the relative condition of the vegetation response as indicated by the NDVI, taking into account the underlying systematic differences in NDVI response related to major differences in the underlying vegetation.

NOAA LAC imagery was captured by the local receiving station (described by Williams & Rosenberg, 1993) at the Meteorological Department of Jordan to enable vegetation monitoring in real-time. A cloud-free image with a nadir view was

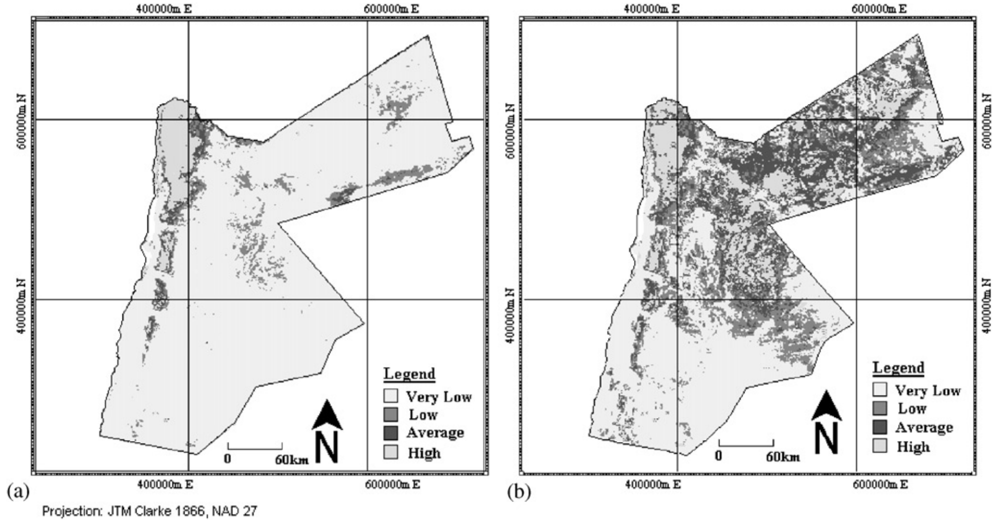

Figure 4. Stratification effect on the VPI map; derived from AVHRR imagery of 25/5/1998, (a) unstratified and (b) stratified using NDVI-response classes.

geometrically corrected using topographic maps and hard copy images of Landsat TM, to create an accurate template. Image-to-image correction was then carried out for the subsequent images. Root-mean-square correction errors were generally less than 1 pixel. All images were re-sampled using cubic convolution with an output pixel size of 1 km. Channels 1 and 2 of the NOAA-AVHRR imagery were radiometrically corrected, and the NDVI was calculated in a manner consistent with the NDVI calculated in the archived imagery. The VPI for each pixel was then determined using the probability curve appropriate to the dekad and NDVI-response class.

Figure 4 shows the influence of the stratification process. In Fig. 4(a), the map was based on the average NDVI response of Jordan as a whole without taking into consideration the different NDVI-response classes. The Badia classes will always be shown as having very low vegetation condition because of the climatic gradient. The VPI map in Fig. 4(b) measures variation of vegetation conditions relative to the individual responses of the NDVI-response classes. Area analysis of the NDVI image of Fig. 4(a) showed that there was very low vegetation in about 87% of the total area, while the VPI map (Fig. 4(b)) showed that the area of very low condition did not exceed 46%. Similar trends were noticed in the other satellite images of both 1997 and 1998. The importance of stratifying the major vegetation zones, as a requirement of vegetation monitoring, is also indicated by previous research (Prince & Tucker, 1986; Tappan *et al.*, 1992; Bastin *et al.*, 1995).

Figure 5 shows the VPI maps which reflected the temporal variations of vegetation condition throughout the 1998 growing season. These variations are attributed to factors related to climate and management. Various studies have shown a strong correlation between the NDVI and rainfall in the semi-arid environments (Kennedy, 1989; Justice *et al.*, 1991; Maselli *et al.*, 1992; Hess *et al.*, 1996; Sannier *et al.*, 1998*b*). According to Millington *et al.* (1994) climatic factors, including rainfall, can explain the AVHRR-NDVI behaviour in drylands. Previous research in the region (Kouchoukos *et al.*, 1998; Smith *et al.*, 1999) indicated a strong correlation between the distribution of the NOAA AVHRR-NDVI and rainfall. The multi-temporal classification of monthly precipitation maps and the NDVI images derived from NOAA GAC followed similar patterns and trends showing the effect of rainfall on vegetation.

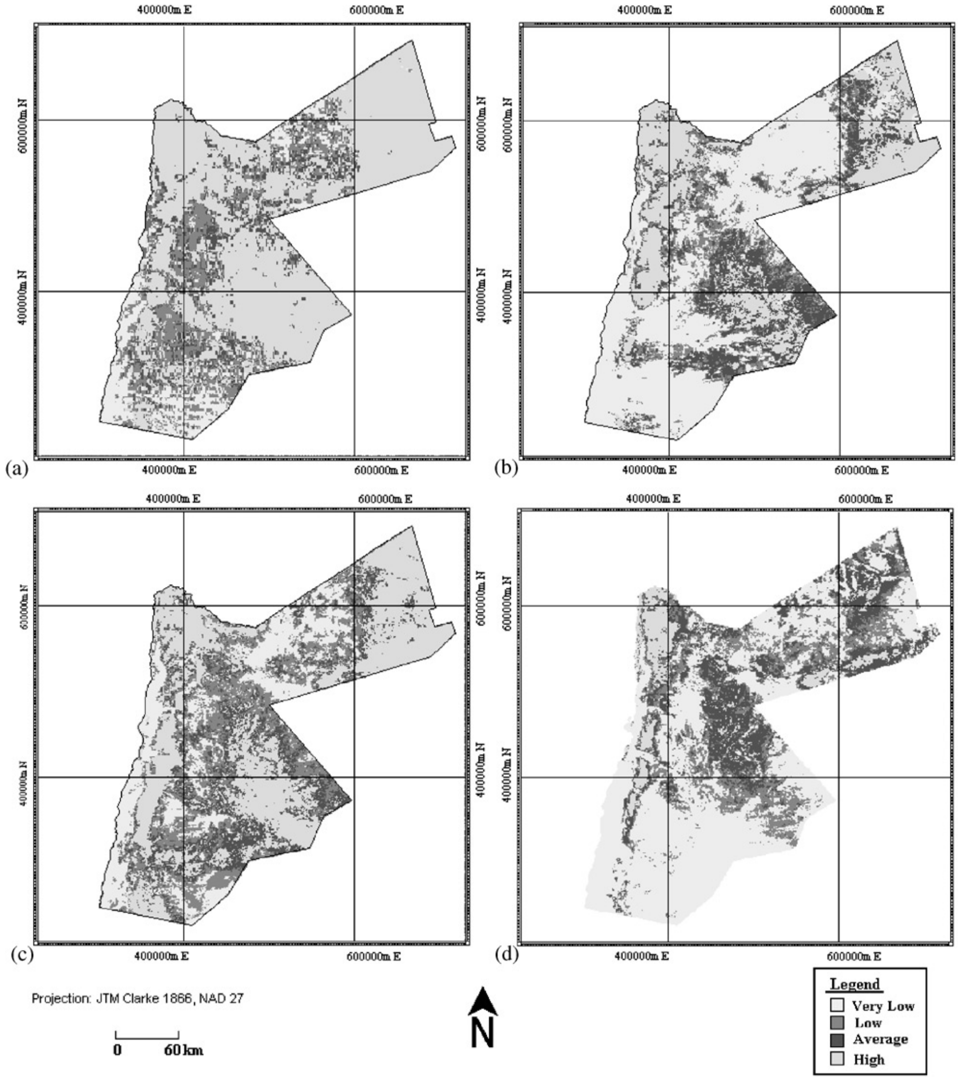

Figure 5. Selected VPI maps for the year 1998: (a) first dekad of January; (b) second dekad of March; (c) second dekad of April and (d) third dekad of May.

In this study, the satellite imagery of January 1998 was acquired a few days after rainfall events. This resulted in high VPI values; dominating 57% of the country (Fig. 5(a)). The VPI map for March (Fig. 5(b)) showed a sharp decrease of the area with high VPI which can be attributed to the overgrazing of natural vegetation. In the second dekad of April (Fig. 5c), the area with high VPI reached 45% of the country after one week of rainfall. In the last dekad of May (Fig. 5d) the area of high VPI did not exceed 14% of the country. Generally, poor vegetation condition dominated large areas of the country in both 1997 and 1998, except in the western part where wheat is grown and irrigated agriculture is practiced.

The VPI maps of 1997 and 1998 showed variation in vegetation condition between both seasons. For example, 82% of the country had a very low VPI in the third dekad of May in 1997. For the same dekad, vegetation condition was relatively better in 1998 as the area of low VPI decreased to 46%. For both years, however, it was noticed

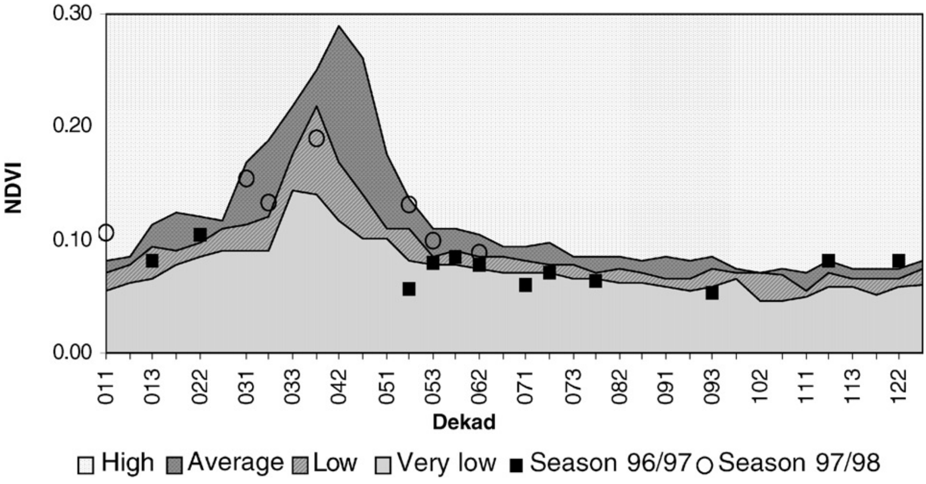

Figure 6. Comparison of the VPI in 1997 and 1998 at Muwaqar catchment.

that after April most of the country was dominated by poor vegetation condition. This is attributed to the end of the agricultural season and the overgrazing of natural vegetation. The latter prevents most natural vegetation from completing its reproductive cycle, thus affecting rangeland productivity and condition negatively.

Sannier *et al.* (1998*b*) also used VPI templates to monitor vegetation conditions at specific locations. The VPI categories for the response-class appropriate to the location are plotted with time to create the template. VPI templates were produced for different study sites within the JAZPP impact zone. Figure 6 shows an example of an area of 8 km $\times$ 8 km covering the Muwaqar Catchment (36°10′E, 31°48′N), 30 km south-east of Amman. Plotting the spatial average NDVI values (derived from LAC imagery) on the 'VPI template' allowed vegetation conditions to be monitored in this study site during the growing seasons of 1997 and 1998. Fig. 6 shows that low VPI values were noticed in Muwaqar during the period from May to September of 1997. The VPI started to increase, above average, after October that year indicating the start of the 1997/1998 growing season. By following similar procedures, it was possible to detect vegetation conditions of different sites within the impact zone of JAZPP.

Monitoring vegetation productivity in the Badia

Overgrazing results in low levels of vegetation productivity inside the Badia rangeland. This factor was considered in this research and biomass sampling was therefore concentrated inside the grazing reserves of Surra, Daba'a, Lajjoun and Ettwana (Fig. 7(a)). Generally, productivity levels inside these reserves are higher than the open range and vegetation is mainly composed of small shrubs and bushes (Tadros & Salem, 1993; Tadros, 1996). Sampling was mainly carried out in the Lajjoun and Ettwana reserves (Fig. 7(a)) because both have areas large enough to be sampled at the level of the LAC imagery and are characterized by relatively homogenous shrub composition. The Lajjoun range reserve (20 km east of Karak City), established in 1980, covers 1100 ha, while the Ettwana Reserve (21 km east of Tafila City), established in 1981, covers 2000 ha. Both reserves have a mean annual rainfall of

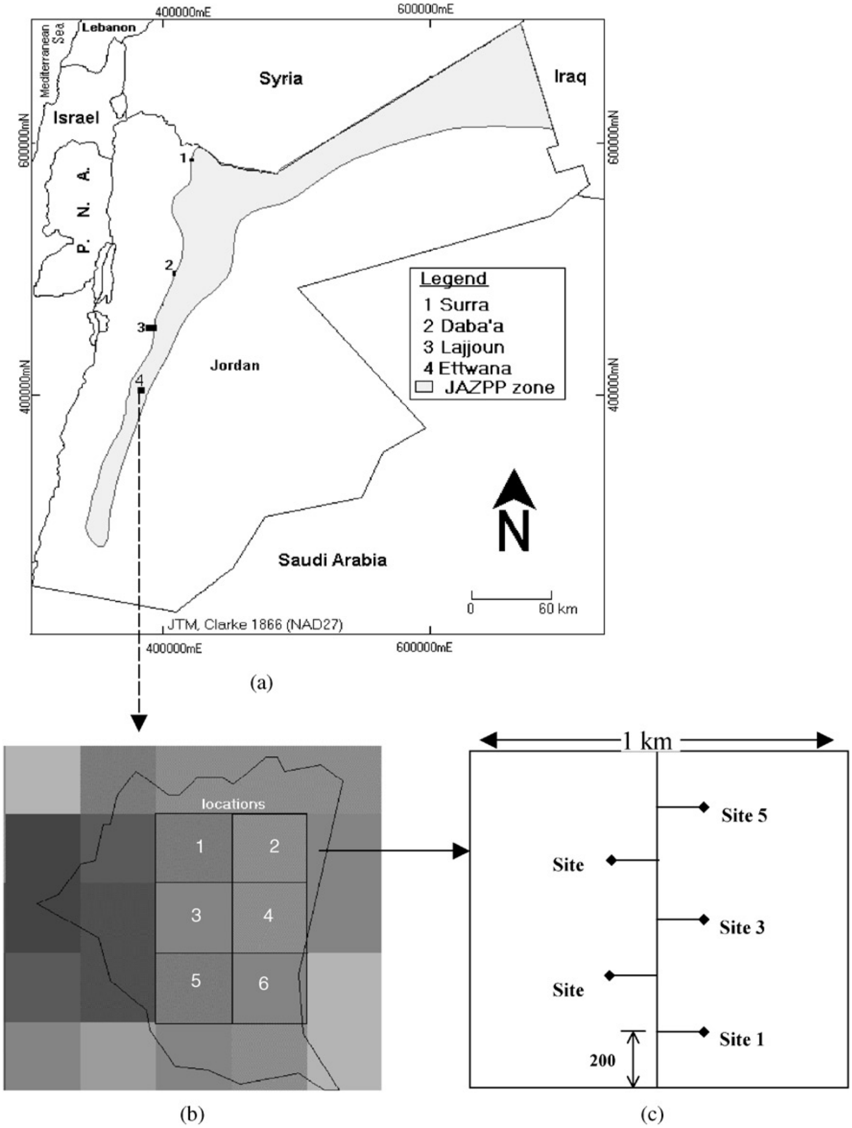

Figure 7. Strategy followed in sampling biomass at the level of NOAA LAC imagery: (a) location of the grazing reserves inside the JAZPP impact zone; (b) Ettwana reserve with sampling locations traced on NOAA imagery and (c) sampling scheme used for selected locations.

150 mm. The dominant natural vegetation in both reserves consists of *A. herba alba* and *Salsola vermiculata*. Both grazing reserves are relatively protected and their general condition is better than the open range. In late April, however, reserves including Lajjoun and Ettwana are opened for grazing.

Cloud-free images with a nadir view were selected and processed 2–3 days before the start of the fieldwork. Processing included geometric correction, re-sampling using cubic convolution, radiometric correction and production of NDVI images, as described above. Sampling sites were located on the processed satellite imagery of

NOAA-AVHRR (as shown in Fig. 7(b)). Four and six sites were traced on the LAC images representing the Lajjoun and Ettwana range reserves, respectively. Sampling sites were traced on hard copy images of SPOT PAN digitally merged with Landsat TM (bands 4, 5, 3), originally used by the National soil map and land use project (NSMLUP) (MOA, 1995). This was carried out to determine precisely the start and the end points for the sampled pixel and to facilitate sampling in the field. In addition, a global positioning system (GPS) and topographic maps of 1:25, 000 and 1:50, 000 scales were used to locate the sampling sites. A sampling strategy was designed with reference to previous research (Taylor *et al.*, 1986; Hiederer & Wyatt, 1990; Garcia, 1993) concerned with the sampling of rangeland vegetation for calibrating NDVI of NOAA AVHRR. Five plots (quadrats), at 200 m intervals, were sampled per square km along the central transect of the site (Fig. 7(c)). The size of the plot was fixed to $5\,\text{m} \times 5\,\text{m}$. The number and the size of plots were based on previous research in the region (Tadros & Salem, 1993; Tadros, 1996).

Vegetation productivity (above-ground biomass) was measured inside the grazing reserves using the reference unit method (Bonham, 1989), which is recommended for sampling sparse vegetation. The method is a combination of direct and indirect methods for estimating vegetation productivity. A small unit of a plant such as a branch is chosen as a reference unit and weighed. The next step is to estimate the number of similar reference units comprising the plants of the same species as the reference unit, within the sampled plot and thus estimate the above-ground biomass for that species. This is repeated for each species within the plot. Some of the sampled plots are then completely clipped and weighed, and linear regression is used to correlate the estimated (from reference units counting) and the actual weight (from clipping). Using the relationship from the previous stage, visual estimates from reference unit counts are corrected to obtain the actual shrub weight of the sampled plot.

The fieldwork started in late March and finished in mid-July 1998. The peak growth of shrubs is usually in summer, but in Jordan it is not possible to reach this stage of growth due to overgrazing. The appropriate time at which maximum growth occurs is usually mid to late April, when shrubs show good vegetative growth before the start of grazing (Tadros, 1996). Therefore, most of the samples were taken in the period between 16th and 20th April when the shrubs were at maximum growth. In order to use a wide range of productivity in the correlation, two more samples were taken in May and three in mid-July.

Nineteen sites (mainly in the Lajjoun and Ettwana reserves) representing the available range of shrub productivity were sampled. Ground data collection took place within three days of the satellite overpass, with the exception of the samples of 16th April, which were collected 5 days after the satellite imagery acquisition. Productivity was calculated on an air-dry basis and ranged from 315 to 1170 $\text{kg}\,\text{ha}^{-1}$, with a mean of 730 $\text{kg}\,\text{ha}^{-1}$. Relatively low levels of productivity were noticed, particularly in the open range. Similar results of productivity inside and outside the Lajjoun reserve were indicated by previous research (Tadros & Salem, 1996). In the Lajjoun reserve, the maximum productivity was obtained in March, while samples after March showed less productivity due to overgrazing.

NDVI values, corresponding to the date and site of sampling, were extracted from the LAC-NDVI images and ranged from 0·07 in the open range to 0·138 in the Lajjoun and Ettwana reserves. Shrub productivity (kg/ha^{-1}) was correlated with NDVI using linear regression analysis. A significant correlation ($p < 0{\cdot}05$, F-test) was observed between air-dry above-ground biomass and the NDVI (Fig. 8). The coefficient of determination (r^2) of 0·75 showed the potential for developing quantitative estimates of shrub biomass from NDVI images. Therefore, the NDVI has the potential to assist the estimation of rangeland carrying capacity in the semi-arid zone of Jordan.

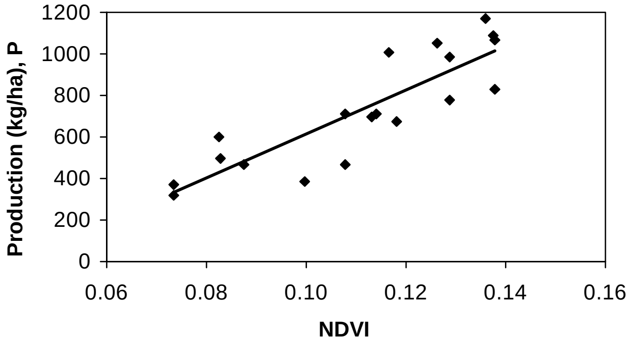

Figure 8. Relation between total biomass (P) kg ha^{-1} and NDVI derived from the AVHRR LAC level imagery for the season 1997/98 (P = 10,563 NDVI−442; $r^2 = 0{\cdot}75$).

Conclusions and recommendations

NOAA AVHRR can monitor successfully vegetation condition and productivity in Jordanian rangelands. The VPI methodology relies on an empirical estimation of the statistical distribution of the NDVI from the time-series. The time-series and subsequent analysis of the statistical distributions should be regularly updated. This enables the VPI to adapt to longer-term changes in the vegetation regime.

In this work, the statistical distributions of the NDVI from the archived data and the NOAA-LAC data acquired from the local receiving station were assumed to be similar. The NDVI values in the archived data (7·6 km spatial resolution) are derived from the original AVHRR data (1–2 km spatial resolution, such as received by the local receiving station in this work) by a combination of sub-sampling and spatial averaging. Thus the distributions will be related. The main difference will be in the variances of the two distributions as the sub-sampling is unbiased and if only sub-sampling had been used, the assumption would be valid. Also, adjacent pixels in satellite imagery are spatially auto-correlated so the influence of the spatial averaging on the variance of the archived data will be reduced. Thus the local variation expressed in the 1km spatial resolution VPI maps is likely to be slightly over-represented, and slightly under-represented when plotting spatially averaged NDVI values of current observations in the templates. A formal assessment of the relationship between the statistical distributions of the archived and original AVHRR imagery should be conducted in future work.

A basic correlation of NDVI with the total biomass of Jordanian shrub rangeland was demonstrated. This work needs to be continued to extend the range of vegetation types included in the analysis and to investigate the temporal stability of the relationship. Relationships between total biomass and usable biomass must also be explored to enable estimates of carrying capacity. This is required to produce productivity maps, which are required to manage the region appropriately.

Finally, the results of the study in 1997 and 1998 showed that the general vegetation condition was below average, particularly in the open range. This work points to the need for good management and planning of the natural resources of the country, including the impact zone of JAZPP. The methodology for monitoring vegetation and vegetation productivity demonstrated could contribute to improving the management of the region by provision of timely spatial information. The Meteorological Department of Jordan could have an important role by processing the NOAA AVHRR satellite imagery to provide users with VPI maps on a regular basis.

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