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NDVI response to rainfall in different ecological zones in Jordan

J. T. AL-BAKRI† and A. S. SULEIMAN‡

†Department of Land, Water and Environment, University of Jordan, Amman 11942, Jordan; e-mail: jbakri@ju.edu.jo

‡Centre for Atmospheric Sciences, Hampton University, 23 Tyler Street, Hampton, VA 23668, USA; e-mail: Ayman.suleiman@hamptonu.edu

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Abstract. The response of NDVI to rainfall was analyzed using NOAA/AVHRR satellite imagery acquired over a time period of ten growing seasons (1981 to 1992) and rainfall data from 16 weather stations in four ecological zones in Jordan. Results of linear regression analysis showed better response of NDVI to cumulative rainfall than to 10-day rainfall with best correlation in the Mediterranean zone. Significant relationships were found between seasonal rainfall and NDVI range (Δ_{NDVI}) with better correlations for logarithmic and power relationships than for linear relationship. A strong linear relationship occurred between the annual rainfall and end-of-season NDVI in the Mediterranean zone and weak or no correlation in other zones. The correlations were improved when the rainfall data were averaged, summed and correlated with the average NDVI. More agreement, however, was observed between the maximum NDVI image and rainfall than for the average NDVI image and rainfall. Results also showed that stratification of the data according to soil type and/or land cover would not necessarily improve the correlation. However, stratification of the data according to ecological zone demonstrated obvious differences between the NDVI-rainfall in the different zones.

1. Introduction

Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) of National Oceanic and Atmospheric Administration (NOAA) satellite, calculated as the difference between the near-infrared and red reflectance values normalized with their sum, is the most commonly used index in vegetation and ecological studies. The high temporal resolution, the good calibration, the adequate spatial resolution and the low price are the main reasons for using AVHRR-NDVI images in many environmental studies (Cracknell 1997).

Rainfall is the most important climatic factor that closely correlates with NDVI, particularly in arid and semi-arid environments where rainfall is the limiting factor for plant growth. Various studies (Du Plessis 1999, Schmidt and Gitelson 2000, Schmidt and Karneili 2000, Suzuki *et al.* 2000, Kawabata *et al.* 2001, Negrón Juárez and Liu 2001, Wang *et al.* 2001) have found significant correlations between NDVI and rainfall in different regions including arid and semi-arid environments. Previous research in the Near East (Smith *et al.* 1999) indicated a strong correlation

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between the distribution of AVHRR-NDVI and rainfall; as the multi-temporal classification of monthly precipitation maps and NDVI images derived from the AVHRR followed similar patterns and trends.

A simple linear relationship between NDVI and rainfall with positive correlation has been found in many studies. Even with few AVHRR observations, the derived NDVI was found to be useful as an indicator of environmental changes because it was sensitive to rainfall in different vegetation zones (Schmidt and Gitelson 2000). According to Nicholson and Farrar (1994), variability of NDVI over Botswana was explained by rainfall as long as rainfall did not exceed 500 mm (saturation response) and types of soils and vegetation were taken into consideration. In east Africa, a distributed lag model showed that only 10% of the variation in 10-day NDVI and 36% of variation in the monthly NDVI were explained by concurrent and preceding rainfall (Eklundh 1998). In Etosha National Park, Namibia, the ability of the AVHRR-NDVI to predict the 10-day and seasonal rainfall was improved when data were smoothed by averaging (Du Plessis 1999). The value of the coefficient of determination (R^2) was improved and reached 0.96 and 0.84 for the averaged data of the cumulative and annual rainfall, respectively. In southern Africa, strong correlations occurred between monthly NDVI (1983–1988) and bimonthly preceding rainfall amounts, attesting a time response of one to two months (Richard and Poccard 1998). The sensitivity to interannual rainfall anomalies was observed only for relative dry areas (mean annual rainfall 300–500 mm) with good correlation regardless of soil type or vegetation formation.

In the Central Great Plains, USA, both biweekly NDVI and precipitation covaried in the same direction for 60–95% of the total land area indicating that precipitation could be a strong predictor of regional spatial patterns of vegetation (Wang *et al.* 2001). In another study (Kawabata *et al.* 2001), monthly AVHRR-NDVI data (1981–1990) were used to analyze interannual trends of vegetation on a global scale. Using linear regression, the study indicated that interannual variations in annual NDVI were attributed to precipitation (R^2 of 0.75 in northern Australia and 0.54 in Argentina). In northeast Brazil, agreement between monthly NDVI (from 1981 to 1993) and rainfall was observed with a time lag of one month (Negrón Juárez and Liu 2001).

Many of the above studies indicated that rainfall and NDVI were strongly correlated. The relationship between rainfall and NDVI, however, was dependent on the NDVI-time series, the ecological zone and its characteristics and to a limited extent on existing vegetation and soil type. Therefore, further studies on the relationship between rainfall and NDVI is needed, particularly in the eastern Mediterranean countries where the presence of vegetation is highly variable through time and space depending on rainfall. This study constitutes one of the attempts aiming to study the relationships between rainfall and NDVI in the different ecological zones in Jordan. The study will provide empirical results of the relationship between rainfall and NDVI in the different ecological zones in Jordan to facilitate the use of AVHRR-NDVI data in related environmental studies.

2. Study area and selected sites

Jordan is located between 29° 11′ N and 33° 22′ N latitude, and between 34° 19′ E and 39° 18′ E longitude with an area of more than 89 thousand km^2. More than 80% of the country's area is arid and receives less than 100 mm annual rainfall with precipitation pattern being latitude, longitude and altitude dependent. Rainfall decreases from north to south, west to east and from higher altitudes to lower ones. Average rainfall ranges from 600 mm/year in the north to less than 50 mm/year in the south and the east. The rainy season is between October and May with 80% of the annual rainfall occurring between December and March. During the rainy season, most of the precipitation is orographic resulting from the passage of frontal depressions across the Mediterranean near Cyprus.

According to GCEP (2000), the country may be divided into four ecological zones or bioclimatic regions (figure 1) as follows:

Mediterranean: restricted to the highlands of Jordan with altitude ranges from 700 to 1750 m above mean sea level and the mean annual rainfall ranges from 300 to 600 mm. This region supports the best natural vegetation in Jordan including forest stands. In addition to natural vegetation, rainfed cultivation of wheat and other field crops, summer crops and orchards is practiced.

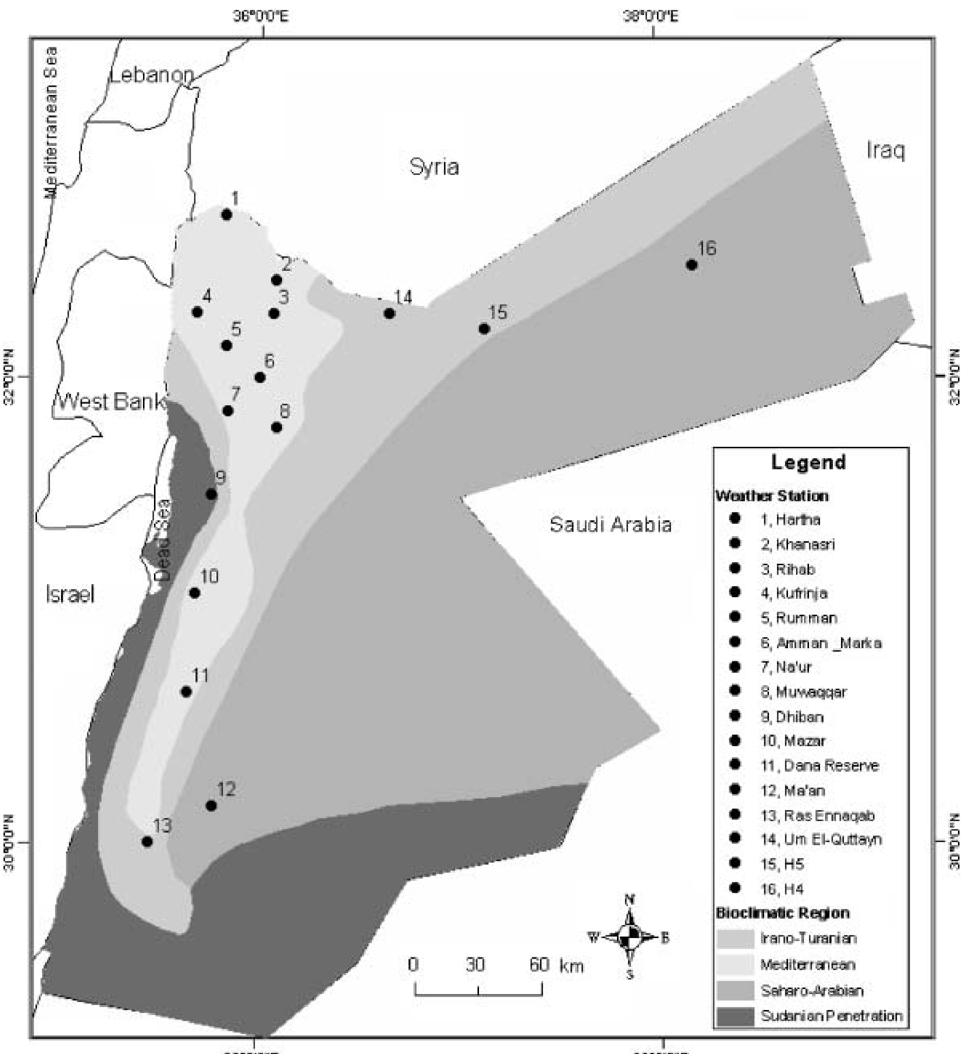

Figure 1. Locations of the study sites (weather stations).

Irano-Turanian: surrounds the Mediterranean region from all sides except the north and characterized by no forest cover. Altitude ranges from 500 to 700 m and annual rainfall ranges from 100 to 300 mm. Vegetation is mainly dominated by low shrubs and bushes (timberless land) and some rainfed barley cultivation.

Saharo-Arabian: comprises most of the country, known as the Badia, with altitude of 600–700 m and a mean annual rainfall of less than 100 mm. Dry hot summer and relatively cold dry winter characterize this region. The region is classified as rangeland and provides home to a wide range of highly diversified adaptive organisms.

Sudanian Penetration: this region provides unique ecosystems as the altitude varies from 400 m below the sea level (at the Rift Valley and Dead Sea, lowest point on earth) up to 1200 m in the south. This region is characterized by very hot summer and warm winter with mean annual rainfall of 50 mm or less. Vegetation is dominated by *Acacia sp.* in the low-altitude region and scattered shrubs in the high-altitude region.

Sixteen weather stations distributed within different sites in Jordan (figure 1) were used in the study. The selection of the stations was restricted by the availability and quality of rainfall data for the corresponding period of archived satellite imagery (1981–1992). The selection was also based on the location of weather station in relation to the centre of the satellite imagery's pixel. This was done to reduce the possible source of error that might result from image georeferencing and the interpolation of pixel's value.

The selected sites were overlaid onto the maps of the ecological zones (figure 1) and soil (MOA 1993) to define the characteristics of the area (7.6 km $\times$ 7.6 km) surrounding each site. Most of the stations were located in the Mediterranean zone and only one station was located within the Sudanian Penetration. Characteristics of each site are shown in table 1.

3. Data Processing and Analysis

3.1. *Rainfall data*

Daily rainfall records of each station were entered from hardcopy reports, provided by the Meteorological Department of Jordan, into spreadsheets. Different functions were applied to calculate the following:

- Ten-day rainfall of the rainy season (October to May) for a ten-year time series from October 1981 to May 1992. This accounted to a total of 240 observations (3 observations/month $\times$ 8 months/season $\times$ 10 seasons) for each station.
- Cumulative rainfall at the end of each 10-day interval for each season for the ten seasons. This accounted to a total of 240 observations (3 cumulative observations/month $\times$ 8 months/season $\times$ 10 seasons) for each station.
- Cumulative average (10-seasons) rainfall, which accounted for 24 observations for each station.
- Monthly average rainfall, which accounted to a total of 80 observations (8 months/season $\times$ 10 seasons) for each station.
- Cumulative monthly rainfall (80 observations for each station).
- Seasonal rainfall for all stations (160 observations) and for each ecological zone (varied depending on the number of stations within each zone).

Table 1. Characteristics of the 16 study sites.

Weather station	Altitude (m)	Dominant soil association*	Dominant land cover/use
Hartha	400–500	Typic and entic xerochrept	Rainfed wheat, rangeland and scattered farms of orchard crops.
Khanasri	740–960	Typic and calcic xerollic xerochrept	Low intensity rangeland mixed with rainfed barley.
Rihab	700–900	Calcixerollic and typic xerochrept.	Rainfed barley mixed with rangeland and limestone rock.
Kufrinja	900–1100	Typic xerochrept	Mixed orchard crops and horticulture, small areas of woodlands and rangeland.
Rumman	680–800	Typic xerochrept	Woodland, mixed orchard crops and rainfed wheat, small area of rangeland.
Amman_Marka	700–800	Xerochreptic and lithic camborthid	Urbanized area in the east, rangeland and limestone rock in the west.
Na'ur	800–950	Calci and typic xerochrept	Rainfed wheat, mixed orchard crops and forests.
Muwaqqar	800–910	Xerochreptic camborthid and calciorthid	Low intensity rangeland with rainfed barley.
Dhiban	745–900	Calcixerollic and lithic xerochrept	Mixed field crops and rangeland.
Mazar	1140–1300	Calcixerollic and vertic xerochrept	Rainfed wheat and small area of rangeland.
Dana Reserve	500–1500	Lithic and calcixerollic xerochrept, Typic calciorthid and camborthid	Woodlands on steep rocks of limestone.
Ma'an	1000–1200	Typic calciorthid and camborthid	Gravel plains with low intensity rangeland.
Ras Ennaqab	1100–1600	Xerochreptic calciorthid and typic torripsamment	Steep limestone and sandstone rocks with scattered bushes, sandstone and Aeolian material on wadis.
Um El-Quttayn	950–1000	Xerochreptic calciorthid and palaeorthid	Rainfed barley, scattered basalt stones and brush rangeland.
H5	700–800	cambic and calcic gypsiorthid	Undulating Quaternary basalt flow with silt filled depressions and very low intensity grass rangeland.
H4	680–700	Typic camborthid	Undulating limestone rock with small silt filled depression and low intensity grass rangeland.

*Based on USDA-SSS (1990).

3.2. *Satellite data Processing*

The archived NDVI images, subset of the NASA Pathfinder AVHRR Land (PAL) archive, were composites of the maximum NDVI value recorded for each 10-day period and originally generated from daily data. The NDVI time series data comprised the GAC (Global Area Coverage) images with a resolution of 7.6 km at a view angle of 35° off nadir and projected to the Hammer-Aitoff projection (Holben 1986, Townshend 1994, Smith *et al.* 1997). For the present study, the NDVI time series included 360 images (August 1981 to May 1992) covering ten growing seasons. The NDVI values for cloudy pixels were linearly interpolated, using the method suggested by Groten (1993). The NDVI values were extracted as spectral profiles from the pixels corresponding to the locations of the different weather stations. The extracted profiles were then arranged in spreadsheets to carry out further analysis.

3.3. *Regression analysis*

Rainfall and NDVI were incorporated in linear regression analysis with rainfall as independent variable and NDVI as the dependent variable. The following relationships were examined:

- Mean seasonal rainfall vs. NDVI range ($\Delta_{NDVI} = NDVI_{max}$-$NDVI_{min}$).
- 10-day rainfall vs. NDVI.
- Average monthly rainfall vs. average monthly NDVI.
- Cumulative rainfall vs. NDVI.
- Cumulative rainfall vs. average monthly NDVI.
- Cumulative average rainfall vs. average 10-day NDVI.
- Seasonal rainfall vs. end-of-season NDVI.

4. Results and Discussion

Analysis of the mean seasonal rainfall (seasons 1982–1991) showed a wide variation in rainfall amounts, 42 mm in Ma'an up to 584 mm in Kufrinja, and NDVI values at the different study sites (table 2). The highest Δ_{NDVI}, occurred in the Mediterranean zone where the relatively high rainfall amounts promoted vegetation growth and cover. It is believed that Δ_{NDVI} approximates the weather driven component of NDVI (Kogan 1990, 1997) where the $NDVI_{min}$ indicates the ecosystem resource while the $NDVI_{max}$ indicates both of ecosystem resource and weather impacts. Results from this study concurred with the above facts as the lowest $NDVI_{min}$ occurred in H5 where the site was dominated by little or no vegetation cover, while the highest $NDVI_{min}$ occurred in Kufrinja where most of the site was covered by evergreen forests, that characterized the Mediterranean zone (GCEP 2000), and orchards that resulted in a higher $NDVI_{min}$ value.

Results of regression analysis between mean seasonal rainfall and Δ_{NDVI} showed significant relationships ($p < 0.05$, $n = 16$) with a relatively high coefficient of determination, with a general trend of increasing NDVI with rainfall amounts (figure 2). Further analysis showed that excluding Kufrinja site from the regression analysis increased R^2 from 0.66 to 0.86. This suggested that either the NDVI response to rainfall reached a threshold value (saturation response) above which no further response was occurring or the NDVI response to rainfall was non-linear. Previous research (Nicholson and Farrar 1994) in the semiarid zone of Botswana indicated a threshold value of rainfall of approximately 500 mm. In this study, an intermediate value of mean annual rainfall between 407 mm (Na'ur) and 584 mm

Table 2. Mean seasonal rainfall (1981–1992) and NDVI values for the 16 study sites.

Station (reference # in figure 1)	$NDVI_{min}$	$NDVI_{max}$	Δ_{NDVI}	Mean seasonal rainfall (mm)
Hartha (1)	0.020	0.527	0.507	392
Khanasri (2)	0.012	0.297	0.285	184
Rihab (3)	0.031	0.273	0.242	209
Kufrinja (4)	0.086	0.438	0.352	584
Rumman (5)	0.023	0.355	0.332	248
Amman_Marka (6)	0.039	0.297	0.258	243
Na'ur (7)	0.039	0.480	0.441	407
Muwaqqar (8)	0.035	0.262	0.227	122
Dhiban (9)	0.027	0.352	0.325	298
Mazar (10)	0.043	0.355	0.312	292
Dana Reserve (11)	0.039	0.227	0.188	221
Ma'an (12)	0.043	0.125	0.082	42
Ras Ennaqb (13)	0.027	0.156	0.129	91
Um EL-Quttayn (14)	0.008	0.277	0.269	135
H5 (15)	0.000	0.102	0.102	88
H4 (16)	0.027	0.129	0.102	85

(Kufrinja) was not available to generalize a threshold value. Therefore, non-linear relationships were applied to NDVI-rainfall and showed that R^2 significantly increased to 0.76 and 0.82 for logarithmic and power relationships, respectively (Figure 2). This suggested that the Δ_{NDVI} response to rainfall was non-linear.

4.1. *Ten-day and monthly relations*

Results of linear regression (table 3) showed weak or no significant correlations between 10-day rainfall and NDVI and between average monthly rainfall and average monthly NDVI. The time series of both rainfall and NDVI were plotted for the different stations to examine the temporal variations in both rainfall amounts and NDVI. (examples are shown in figure 3). Generally, sharp peaks with better NDVI response to rainfall were observed in the Mediterranean sites when compared with other ecological zones. The lowest R^2 between NDVI and rainfall occurred in the arid areas of Ma'an, the lowest rainfall record, and H5 where both time series were nearly flat.

Further inspection of rainfall and NDVI time series showed an obvious shift between their peaks with NDVI being lagged behind rainfall. The shift varied from one station to another and within the same ecological zone and for the same site from one year to another. Therefore, the preceding rainfall (cumulative effect) was considered and incorporated with NDVI in the linear regression analysis. An obvious improvement in R^2 was obtained in the different sites (table 3) with agreement between cumulative rainfall and NDVI peaks for both 10-day and monthly correlations. The relatively high rainfall amounts in the Mediterranean sites resulted in a higher increase of R^2 compared with the other ecological zones. The maximum R^2 value occurred in Mazar site while the minimum values occurred in the arid site of H4 and the semiarid site of Dhiban for cumulative 10-day and monthly relationships, respectively. These results concurred with the findings reported by previous research (Hess *et al.* 1996, Eklundeh 1998, Negrón Juárez and Liu 2001) in different ecological zones as NDVI showed better response with cumulative rainfall.

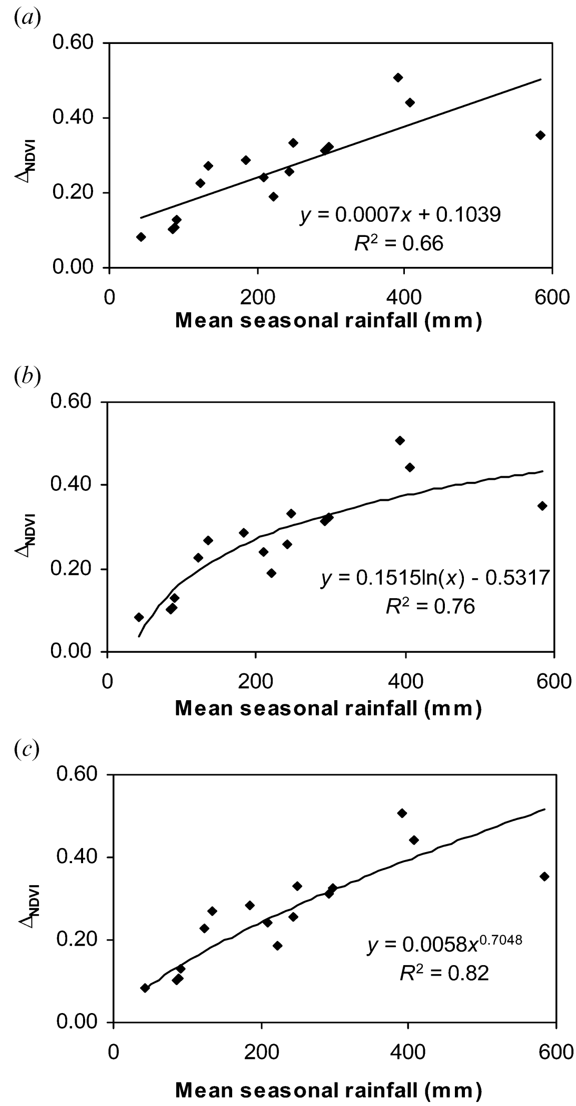

Figure 2. Relationships between mean seasonal rainfall and Δ_{NDVI}. (*a*) linear, (*b*) logarithmic and (*c*) power.

The effect of time lag on NDVI-rainfall relationship was also investigated for both 10-day and monthly correlations. Results showed no obvious improvement in correlation when different lags (composition periods) were considered. In the Kufrinja site, for example, the correlation between the 10-day rainfall and NDVI did not improve for a 20-day lag (figure 4) or other composition periods. Similar results were obtained when a lag period was applied for the 10-day and cumulative rainfall data for all sites. Generally, the R^2 value tended to decrease when the composition period increased for both the 10-day and monthly correlations. Although these results did not confirm with those of Richard and Poccard (1998) and Negrón Juárez and Liu (2001), these could be attributed to the relatively short growing season with few rainfall events in most years. The time lag under such conditions was expected to have a weak influence on correlation coefficients (Wang *et al.* 2001).

Table 3. Coefficient of determination (R^2) for the different correlations between rainfall and NDVI. The numbers in the column header indicate the investigated relationships (bottom of the table).

Station	1	2	3	4	5
Hartha	<0.01	$<0.01^{ns}$	0.46	0.52	0.73
Khanasri	$<0.01^{ns}$	$<0.01^{ns}$	0.42	0.44	0.78
Rihab	$<0.01^{ns}$	$<0.01^{ns}$	0.56	0.61	0.76
Kufrinja	0.02	0.01	0.45	0.52	0.86
Rumman	<0.01	0.01	0.45	0.47	0.88
Amman_Marka	<0.01	0.02	0.49	0.59	0.79
Na'ur	0.03	0.05	0.57	0.58	0.79
Muwaqqar	<0.01	0.02	0.46	0.54	0.85
Dhiban	$<0.01^{ns}$	$<0.01^{ns}$	0.18	0.13	0.79
Mazar	0.01	0.01^{ns}	0.59	0.62	0.82
Dana Reserve	0.01	0.01	0.50	0.54	0.88
Ma'an	<0.01	0.07	0.26	0.39	0.77
Ras Ennaqb	$<0.01^{ns}$	$<0.01^{ns}$	0.32	0.39	0.85
Um EL-Quttayn	0.01	0.01	0.39	0.38	0.80
H5	0.01	$<0.01^{ns}$	0.20	0.26	0.84
H4	0.01	$<0.01^{ns}$	0.16	0.21	0.74

10-day rainfall versus NDVI, $n=240$.
Average monthly rainfall versus average monthly NDVI, $n=80$.
Cumulative rainfall versus 10-day NDVI, $n=240$.
Cumulative rainfall versus average monthly NDVI, $n=80$.
Cumulative average rainfall versus average 10-day NDVI, $n=24$.
ns: not significant at 0.05 *P*-level.

4.2. *Spatial patterns of NDVI and rainfall*

For better understanding of the NDVI response to rainfall, images of average, maximum and minimum NDVI were compared with the map of mean annual rainfall (figure 5). It was noticed that the maximum NDVI followed a similar pattern of mean annual rainfall with high agreement in the Mediterranean zone and exceptions in the south where irrigation projects were taking place in the Disi area. The pattern of average NDVI roughly resembled that of rainfall and many extreme events (details) of NDVI were lost. These findings indicated that averaging the NDVI values to remove inter-annual variations and residuals (Du Plessis 1999) might result in loss of useful information. The increase of R^2 in this study due to data averaging (table 3, column 5) might be attributed to the considerable decrease of observation rather than the removal of outliers. In general, more details could be seen in the maximum-NDVI map in Mediterranean sites of relatively good rainfall and vegetative cover while less NDVI response occurred in the Saharo-Arabian and Sudanian Penetration zones, where annual rainfall was less than 100 mm. The NDVI response to average rainfall, on the other hand, was low for all areas receiving less than 400 mm. The spatial pattern of maximum NDVI in addition to the results of the Δ_{NDVI}–rainfall would confirm the use of NDVI range in vegetation and environmental studies in the region (Schmidt and Gitelson, 2000).

4.3. *Effect of stratification*

The relationships between cumulative rainfall with NDVI and the seasonal rainfall with the end-of-season NDVI were investigated for the different ecological zones by aggregating data from the different sites within the same zone. Results

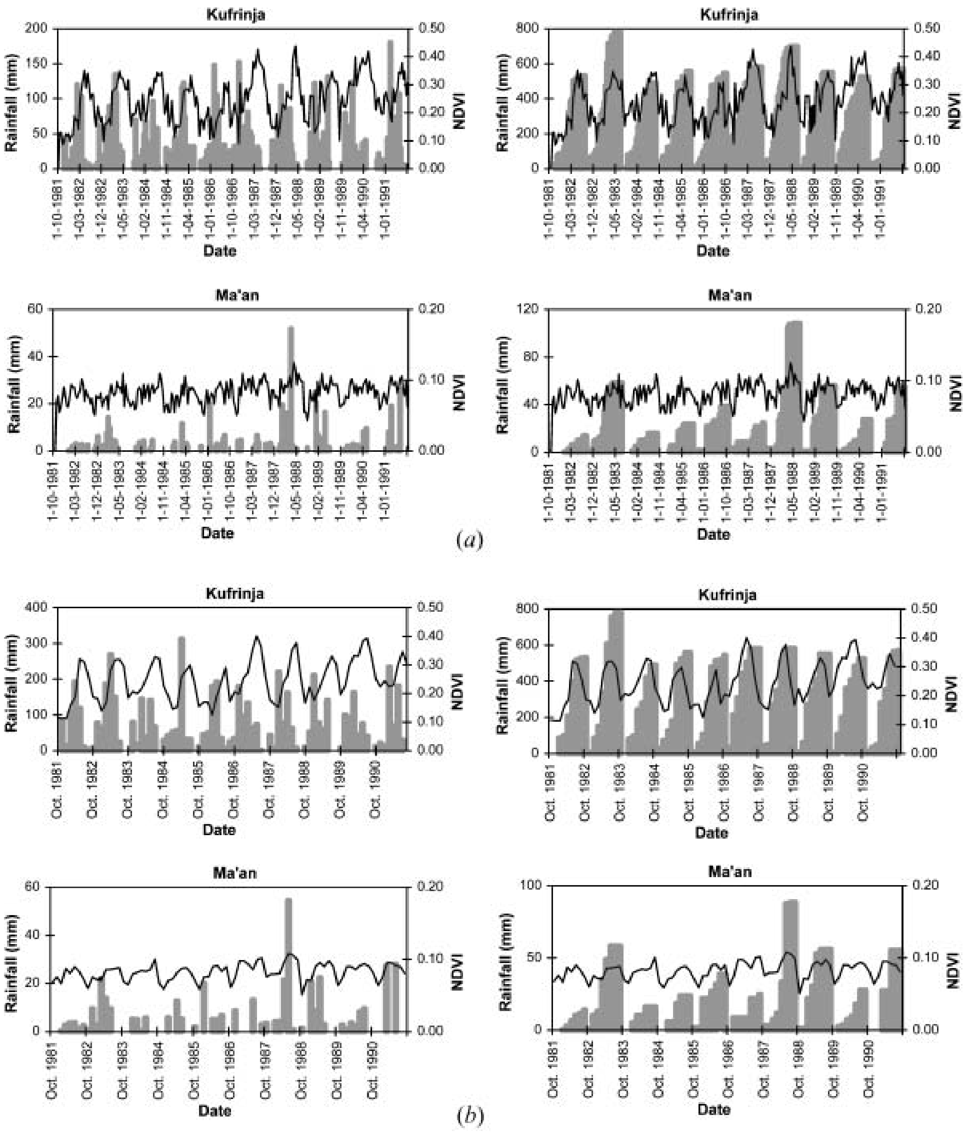

Figure 3. Examples of the response of (*a*) 10-day NDVI to rainfall (left) and to cumulative rainfall (right), (*b*) average monthly NDVI to average monthly rainfall (left) and to cumulative rainfall (right). ▬ rainfall; —— NDVI for Kufrinja and Ma'an.

showed significant linear relationships between the seasonal rainfall and the end-of-season NDVI in all ecological zones except the Sudanian Penetration where the number of observations was only ten (figure 6).

The R^2 values were higher in Mediterranean zone than in the other ecological zones (table 4). The weak correlations in the arid zones of Irano-Turanian and Saharo-Arabian and the semiarid Irano-Turanian zone could be attributed to the relatively low rainfall amounts, the short growing season (GCEP 2000) and the overgrazing of the natural vegetation shortly after greening. The relatively longer growing season and the type of land cover in the Mediterranean zone, on the other hand, resulted in a stronger correlation between rainfall and NDVI.

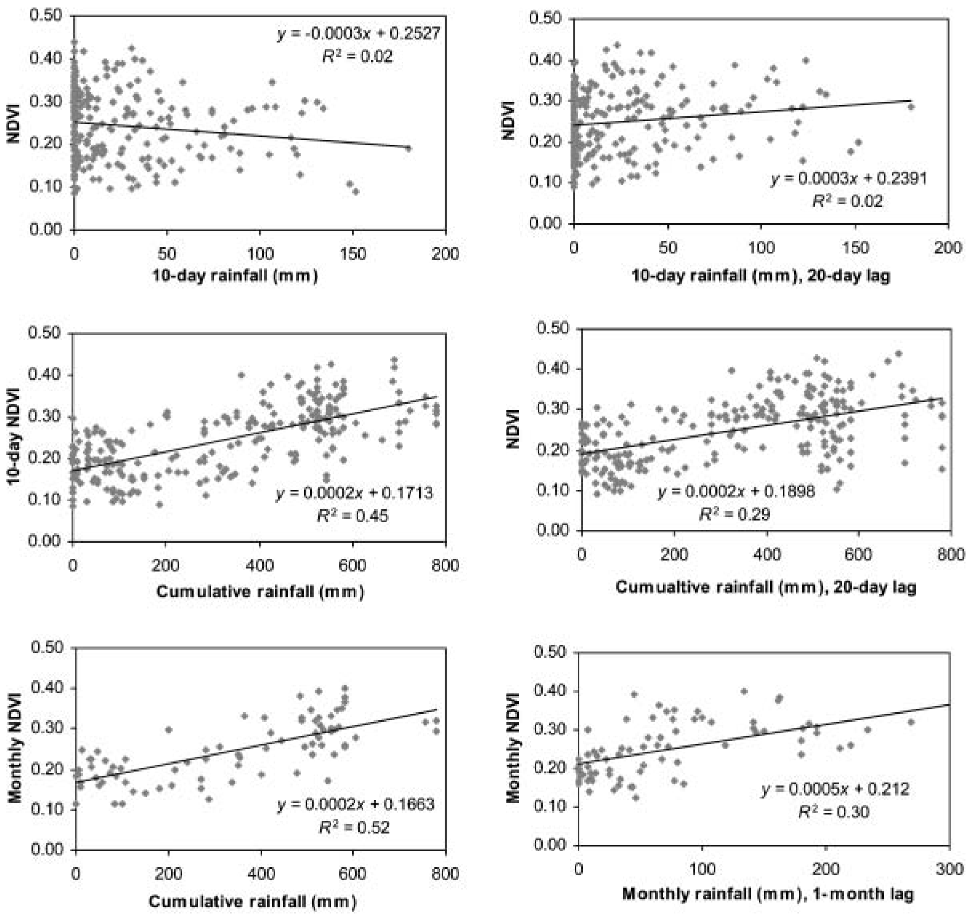

Figure 4. Examples on the relationships between rainfall and NDVI in Kufrinja station (left) with different lags (right).

In general, the trend of increasing NDVI and end-of-season NDVI with cumulative rainfall was seen in all the different ecological zones. Analysis of the linear regression coefficients (table 4) showed wider confidence intervals (CI) for the rainfall and end-of-season relationship when compared with the cumulative rainfall-NDVI relationship, although the standard errors of both relationships were closely matching. This could be attributed to the high number of observations in the case of cumulative rainfall-NDVI relationship and the low number of observations in others.

Interestingly enough, the intercepts and their CI were positive in all ecological zones. These relatively low NDVI values (<0.10) might represent the periods of absence of vegetation and effect of dominant soil background on NDVI, particularly in the Saharo-Arabian and the Sudanian Penetration zones. Therefore, the possibility of stratifying the data according to the different soil types and existing land cover/use was investigated.

Results for the aggregated data in Kufrinja and Rumman, having similar soil type as shown in table 1, will be discussed as an example. Correlating the cumulative rainfall data and NDVI aggregated from both of Kufrinja and

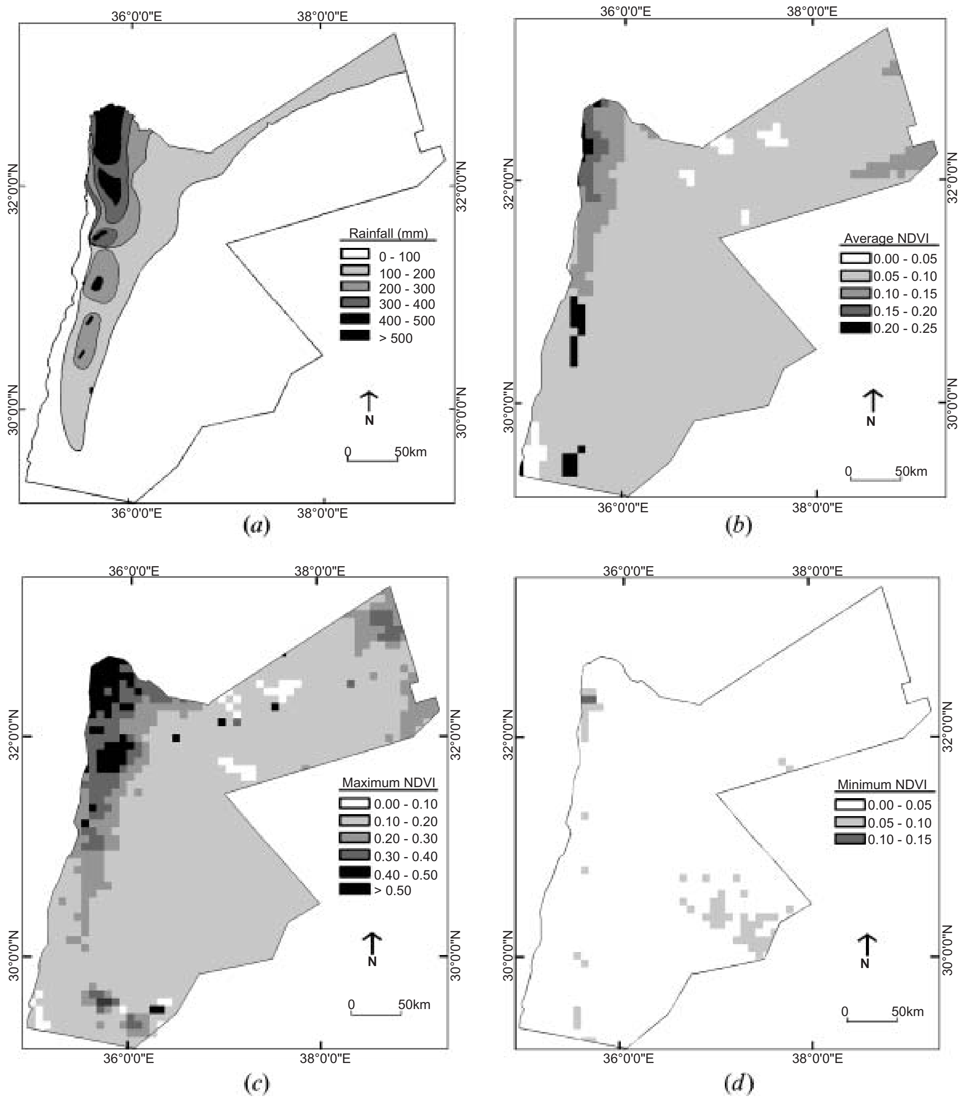

Figure 5. Spatial distribution of (*a*) mean annual rainfall, (*b*) average NDVI, (*c*) maximum NDVI and (*d*) minimum NDVI for Jordan.

Rumman resulted in a little improvement in R^2, 0.54 for aggregated data compared with 0.52 and 0.47 for each site (table 3, column 4), respectively. Similar findings of little or no improvement were also observed when the data were stratified and aggregated according to soil and/or land cover types. These results, confirmed with that of Richard and Poccard (1998) and disagreed with that of Nicholson and Farrar (1994), could be attributed to the large pixel size at the GAC level, which inevitably included a mixture of soils and land cover types.

Finally, the effect of pixel's location selection was investigated for selected weather stations; two examples for Ma'an and Rumman sites will be discussed. In both stations, no significant changes were observed when the linear regression results for the extracted NDVI were compared with the NDVI values linearly

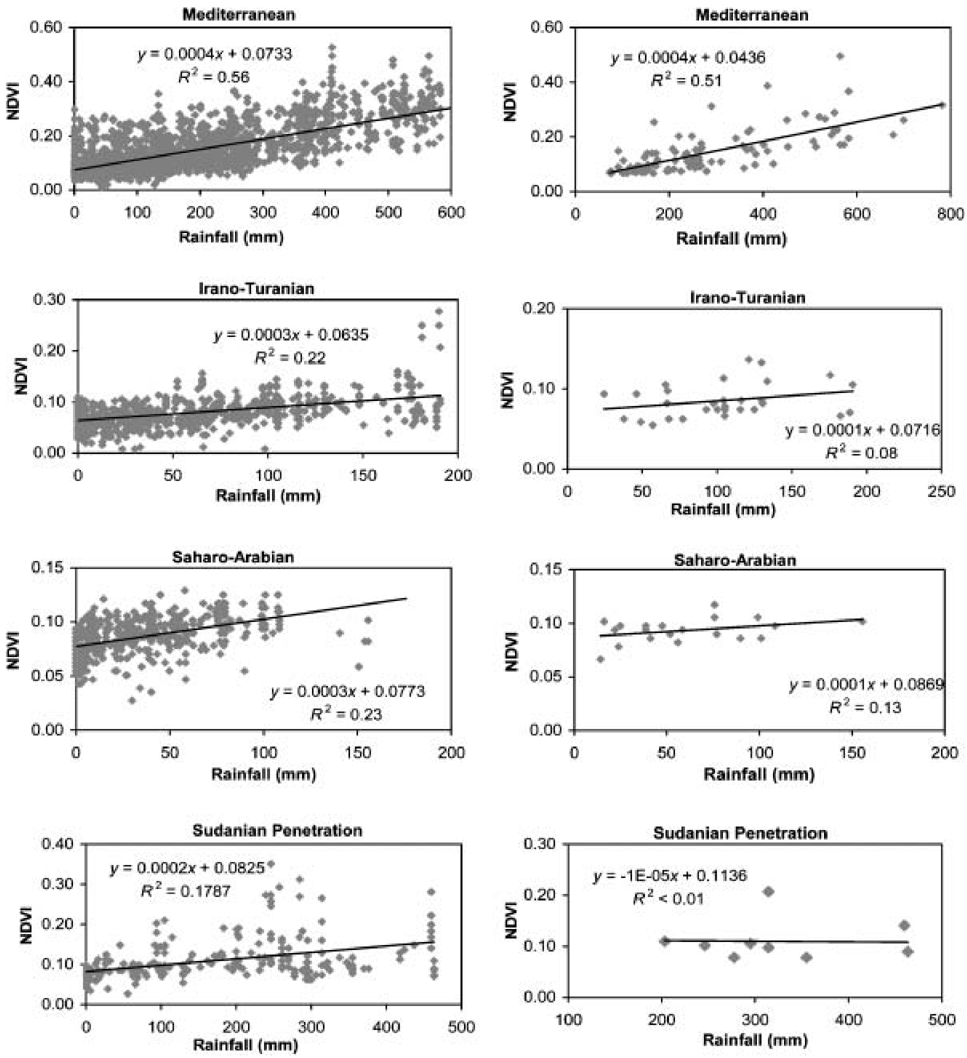

Figure 6. Relationships between cumulative rainfall with 10-day NDVI (left); seasonal rainfall with the end-of-season NDVI (right) in the different ecological zones.

interpolated from the eight neighbour pixels. The R^2 for NDVI-cumulative rainfall relationship changed from 0.26 to 0.28 and from 0.45 to 0.46 in Ma'an and Rumman, respectively. No significant changes were also observed for other sites or the other investigated relationships. These results can be explained by the selection of the weather stations, which was limited to 16 stations that were close to the centre of the corresponding pixel to avoid expected errors that might result from interpolating the NDVI value.

5. Conclusions

Results from the study showed that rainfall explained the NDVI behaviour in the different ecological zones in Jordan, with different relationships and correlations obtained, depending on the investigated relationships between NDVI and rainfall. Good correlation occurred between cumulative rainfall and NDVI for

Table 4. Linear regression analysis of cumulative rainfall versus. NDVI and seasonal rainfall versus end-of-season NDVI for the different ecological zones.

	Cumulative rainfall versus 10-day NDVI				Seasonal rainfall versus end-of-season NDVI			
Bioclimatic zone	Intercept ($\times 10^{-2}$)	Slope ($\times 10^{-4}$)	R^2	SEYX ($\times 10^{-2}$)	Intercept ($\times 10^{-2}$)	Slope ($\times 10^{-4}$)	R^2	SEYX ($\times 10^{-2}$)
Mediterranean	7.33 (7.03–7.63)*	3.82 (3.69–3.96)	0.56	5.27	4.36 (2.08–6.64)	3.52 (2.82–4.21)	0.51	5.61
Irano-Turanian	6.35 (6.07–6.62)	2.58 (2.22–2.94)	0.22	2.55	7.16 (5.12–9.20)	1.33 (−0.48–3.15)	0.07	2.10
Saharo-Arabian	7.73 (7.54–7.93)	2.52 (2.10–2.94)	0.23	1.53	8.69 (7.70–9.67)	1.07 (−0.33–2.46)	0.13	1.07
Sudanian Penetration	8.25 (7.33–9.18)	1.58 (1.15–2.02)	0.18	4.74	11.36	−0.11	$<0.01^{ns}$	4.10
All zones	6.88 (6.72–7.03)	3.58 (3.49–3.67)	0.54	4.33	5.67 (4.35–7.00)	2.99 (2.52–3.47)	0.50	4.93

R^2 = coefficient of determination.
SEYX = standard error of *y* predicted by *x* at 0.05 probability level.
ns: not significant at 0.05 *P*-level.
*: The 95% confidence interval for significant correlations.

both 10-day and monthly data with a trend of increasing NDVI with rainfall. In general, better correlation between cumulative rainfall and 10-day NDVI was observed in the Mediterranean zone than in the other ecological zones. Similar trends, with wider confidence intervals for linear regression coefficients, were obtained for the seasonal rainfall and end-of-season NDVI.

Results indicated a strong relationship between the NDVI range and seasonal rainfall confirmed by a closer spatial pattern of the maximum NDVI image and rainfall map. This point is important in the application of NDVI data in vegetation and environmental studies such as vegetation monitoring and land cover mapping. The vegetation condition indicators that are based on the comparison of current NDVI with mean NDVI images (Hutchinson 1991, Lambin *et al.* 1993), for example, are expected to be less sensitive to vegetation changes in the ecological zones presented in this study. Therefore, the application of other vegetation condition indicators (Kogan 1990, Sannier *et al.* 1998, Al-Bakri and Taylor 2003) that are based on NDVI range and distribution is expected to be more accurate. Similarly, the use of the 8-km NDVI maximum images for mapping global land cover (DeFries *et al.* 1998, Hansen *et al.* 2000) is expected to produce more detailed maps than the average NDVI images.

Results also indicated that the stratification of the study area according to soil type and/or vegetation type did not improve the correlation significantly in most of the sites. Stratification of the data according to the ecological zone showed obvious differences between the NDVI-rainfall in the different zones. Thus, the research emphasized the need to calibrate these relationships for each ecological zone.

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