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Spatial Response of Vegetation to Precipitation in Dry Lands of Kazakhstan: Combination of Remote Sensing Data with Climate Records

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Abstract

This study analysed spatial responses of vegetation to precipitation using 10-day images of Normalized Difference Vegetation Index (NDVI) derived from the Advanced Very High Resolution Radiometer (AVHRR) and rainfall records collected at 9 climate stations throughout a large semi-arid region in Central Kazakhstan. The response of NDVI to precipitation was estimated by calculating coefficients of spatial correlation between corresponding gridded maps of NDVI and rainfall during the period 1985-2001. The analyses were carried out at two different spatial scales (the whole study region and the scale of individual vegetation type) and two temporal scales (annual and within each of the individual growing seasons). The results proofed a strong relationship between NDVI and precipitation: NDVI and precipitation co-varied in the same direction (either positive or negative) at all spatial and temporal scales upon study. However, the response of vegetation to precipitation exhibited significant spatial and temporal variability. At the scale of the whole growing season, the NDVI-rainfall correlation increases from desert to semi-desert and steppe vegetation. On the contrary, at the within-season scale, desert vegetation demonstrated a much stronger dependence on precipitation than other two vegetation types. The relationships between NDVI and precipitation were found to be strongly non-linear: the upper threshold for the linear relationship is about 250 mm for growing season and 15-30 mm for 10-day rainfall amount. Above this threshold, the response of vegetation to precipitation substantively decreases.

Keywords: Kazakhstan, Drylands, NDVI, AVHRR, Vegetation response, Correlation analysis

INTRODUCTION

The satellite-derived Normalized Difference Vegetation Index (NDVI) has proven to be a robust indicator of terrestrial vegetation productivity. The correlation between NDVI and above-ground biomass is well established [1, 2, 3]. Precipitation and temperature are two major climatic factors which strongly influence both temporal and spatial patterns of vegetation productivity. Temporal and spatial correlations between NDVI and climatic factors are investigated in many research works. Particularly well correlation in the arid regions, both spatial and temporal, show NDVI and rainfall [4, 5, 6], the relationship between NDVI and temperature are reported to be weaker but also significant [7, 8, 9, 10]. Some scientists derived also high correlation between NDVI and potential evapo-transpiration [11], between NDVI and soil moisture [12]. However, there were studies indicated opposite results: the studies conducted by [13] and [14] for China found a leading role of temperature by controlling vegetation patterns, and [15] reported to find no significant correlation between NDVI and rainfall in East Africa.

Numerous studies have suggested a linear relationship between NDVI and climate predictors. Theoretically, NDVI can be considered as climatic recorder, mainly as a rainfall recorder. This assumption was used in various drought watching and drought early warning systems [16, 17]. However, the relationship is linear only in a limited range of rainfall conditions. The upper thresholds for the linear relationship between NDVI and rainfall were reported to be approximately 500 mm/yr for semi-arid Botswana [18], 700-800 mm/yr for Senegal [6], and 450-500 mm/yr for China [13]. Above these limits, NDVI increases with rainfall only at a slower rate or even decreases.

The response of NDVI to rainfall and temperature is dependent on vegetation types and varies by geographical region. Woodland and forest vegetation shows a lesser correlation between NDVI and climate factors. Shrubs and desert vegetation patterns are reported to higher correlate with temporal and spatial variations of climate factors. Vegetation patterns in steppe grassland and savannah evident the highest correlation with that of rainfall and temperature [6, 9, 13]. [18] reported for Botswana the response of NDVI to rainfall to be more dependent on soil types than on vegetation types.

The objective of this study was to investigate the spatial variability of vegetation conditions and its relationship to rainfall variability in a semi-arid region of Central Kazakhstan. This study aimed to answer the following questions:

(a) How strong are spatial patterns in NDVI affected by the patterns in precipitation?

(b) Is the response of vegetation to precipitation stratified by vegetation type?

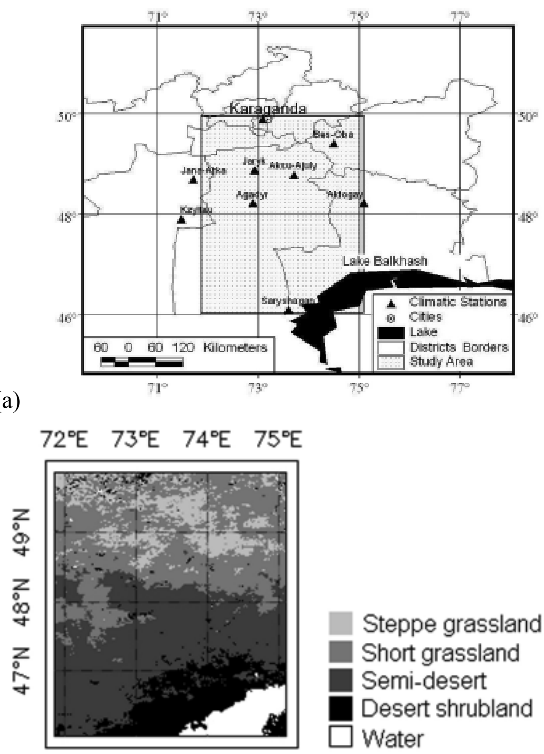
(c) Is the effect of precipitation on NDVI constantly or it changes between different periods of growing season and varies from year to years?

(d) What are the thresholds values of precipitation beyond which the response of vegetation to precipitation is saturated?

To address these questions, we examined the interrelationships between NDVI and precipitation on 10-day and annual time scales over the course of 16 years (1985-2001) using correlation and time-series analysis. We analysed the within-season and seasonal influences of precipitation on spatial patterns of NDVI for both the entire study region (global relations) and for various vegetation types for every year of the study period.

STUDY AREA

The study area is located in the middle part of Kazakhstan between 46 and 50° northern latitude and 72° and 76° eastern longitude and encompasses the south-western part of the Kazakh Hills and its southern margin (Figure 1, a). It comprises the whole area of the Shetsky *raion* (district) in Karaganda *oblast'* (province) and the bordered areas of the neighbouring *raions*. The climate of the region is dry, cold and high continental. Average annual precipitation is above 250-300 mm per year in the north of the study area, and below 150 mm in the south. The most part of precipitation falls during warm period from March to October. Inter-annual rainfall variation has a coefficient of variation of 20-35 %. The region is often affected by drought hazard. During the time period of our study, the region experienced successive dry years 1985, 1986, 1995 and 1997, and successive wet years 1987, 1988, 1993, 1996 and 1998. The temperature amplitude is relative high: average January temperature is below –12° C and average July temperature is about 26-28° C. The growing season starts in April and continues till October.



(a)

(b)

Figure 1. A map of the study region with locations of the climate stations (a), and a map of the land cover in the study area (b).

Due to its geographic location the study area shows a wide spectrum of vegetation communities from various geographical zones: desert, semi-desert and steppe vegetation types are presented here (Figure 1, b). The desert zone is dominated by sagebrush and perennial saltwort associations. The most spreading vegetation species here are *Artemisia terrae-albae, Artemisia pauciflora.* In basins, were solonchak and solonetz develops, the halophytic species such as *Anabasis salsa, Salsola orientalis, Artiplex cana* and *Salsola arbusciliformis* are prevalent. The semi-desert type of vegetation is a gradual transition from desert to steppe type. The semi-desert has a complex combination of real steppe turf grasses and semi-shrubs with halophytes. This zone is covered by shrubs such as *Artemisia pauciflora, Artemisia incana, Artemisia lessingiana*, and grasses such as *Festuca sulcata* and *Stipa lessingiana*. The northern section of the study area lays in the dry steppe zone, were dominate short grassland species such as *Festuca sulcata, Stipa capillata, Stipa lessingiana* and *Filipendula ulmaria.*

DATA USED IN THE STUDY

NOAA AVHRR NDVI

We used the Normalized Difference Vegetation Index (NDVI) derived by the Advanced Very High Resolution Radiometer (AVHRR) launched by the National Oceanic and Atmospheric Administration (NOAA). The data, at 8-km spatial resolution, are originally processed as 10-day composites using the maximum value procedure to minimize effects of cloud contamination [19] and cover the period from 1985 to 2003. Unfortunately, the long-time series of satellite data always remain noises associated with residual atmospheric effects, orbital drift effects, inter-sensor variations, and stratospheric aerosol effects [20, 21] that can produce significant errors by applications. In order to reduce these noises, we have made a calibration of the GIMMS NDVI data using a method described by [22]: the NDVI time-series were calibrated against three time invariant desert targets located in the Big Arabian Desert, Nubian Desert and Taklimakan Desert. The vegetation-free surface of these desert targets considered to be stable throughout the analyzed time-period and should exhibit NDVI with value of near zero. Any temporal deviations of the NDVI value from zero have to be attributed to a non-vegetation noise and are to be corrected. This method removes effects of sensor degradation remaining in the original NOAA AVHRR NDVI data and corrects drift between different sensor systems. In addition to that, we removed noisy pixel areas characterized by exceptionally low NDVI values relatively to their pixel neighbourhood. These pixels were replaced by a mean value calculated from their spatial neighbourhoods.

Rainfall data

Rainfall data were retrieved from the annual statistics by the National Hydrometeorological Centre of Kazakhstan (NHMCK). These data contained 10-day records of 9 climate stations placed in the study area. The data cover growing seasons (April-October) throughout the period 1985-2001. 10-day precipitation gridded maps for every year from the study period were prepared using kriging with external drift (KED). There are prominent anomalies in the patterns caused by influence of relief on precipitation distribution. The magnitude of elevation in the study region is about 700 m, the altitude ranges from 350 m to over 1000 m. Therefore, this external explanatory factor for spatial distribution of climate variables had to be incorporated in the kriging model by preparing gridded maps. In order to assess the accuracy of the data preparation, we randomly reserved 3 weather stations from the interpolation for one of the 10-day from every year and recorded values. Average error was less than 6%. It means that the used extrapolation approach worked effectively.

METHODS

We examined spatial relations between NDVI and precipitation stratified according to land cover categories shown in Figure 1 (b). Correlation coefficients between NDVI and precipitation were calculated for the study area by directly comparing corresponding pairs of NDVI and precipitation maps. The primary goal of the analyses was to evaluate the correspondence between NDVI spatial patterns and precipitation variation. Analyses examined relations both within growing seasons (within-season) and between seasons (seasonal). Within-season analyses compared different 10-day periods within the same growing season. Inter-annual analyses compared NDVI, precipitation and temperature values between different years. For each year NDVI was averaged through growing season (April-October), precipitation was accumulated for the entire growing season.

Recent literature reported about time lags between precipitation events and the response of vegetation to such events [6, 9, 11, 12]. For each 10-day period in the growing season (April to October), NDVI-precipitation correlation coefficients were calculated with different time lags (zero to five 10-day period lags, i.e. each 10-day NDVI image was compared with a total of 6 different precipitation patterns. Thus, we were able to assess the time-scale of precipitation that most strongly influences NDVI spatial patterns.

Correlation coefficients between growing season average NDVI images of each year and precipitation maps were calculated. In order to evaluate the time period over which precipitation most strongly influences overall productivity, a series of analyses were performed using maps of precipitation totalled over different number of years, ranging from 1 to 5.

In order to investigate within-season and seasonal variations of the vegetation response to precipitation, we examined time-series of correlation coefficients between NDVI and precipitation at the within-season and seasonal time-scale. In order to test whether the response of vegetation to precipitation is linear or non-linear, we investigated relations between values of the NDVI-precipitation correlation coefficient and amount of precipitation. For that, we drew values of correlation coefficient versus rainfall amount at scatter plots and analysed them visually. On this way we determined the value thresholds above that the response of vegetation to precipitation saturates. This operation was carried out for both within-season and seasonal time-scales.

RESULTS

Spatial patterns of Normalized Difference Vegetation Index (NDVI) and precipitation in the study area

There are two factors influencing the spatial patterns of vegetation and precipitation in the study area: the south-north direction and altitude gradient. Generally, the spatial variance of NDVI and precipitation is strongly predicted by the south-north factor, but the relief conditions slightly distort this rule and make the spatial patterns more difficult. Vegetation and rainfall variable display similar spatial patterns. Average precipitation increased markedly from south to north: from about 100 mm in the desert to over 280 mm in the steppe zone (Figure 2, b). The 10-year average of NDVI ranges from less than 0.05 in the southern area of the study region to more than 0.30 in the steppe zone (Figure 2, a).

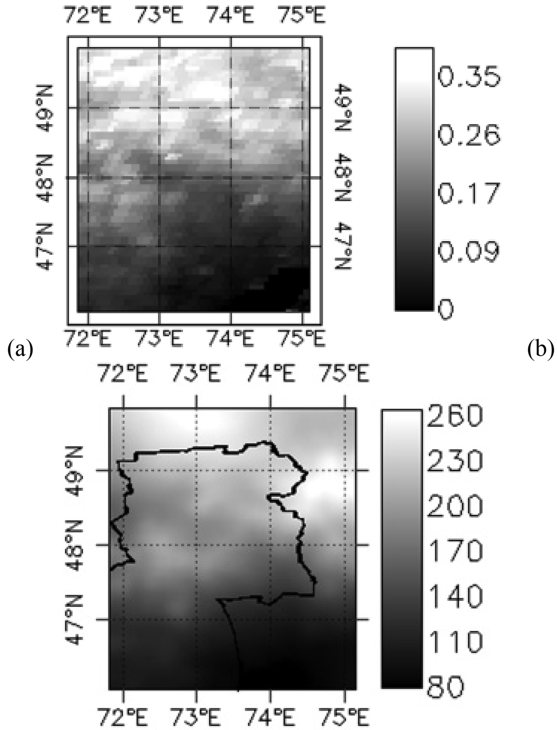


Figure 2. Maps showing the spatial distribution of mean growing season NDVI calculated from the average of 8-km NOAA AVHRR for the period 1985-2003 (a) and total amount of rainfall for the same period (b).

Growing season relationships between NDVI and precipitation

NDVI-rainfall correlation coefficients

Correlation coefficients between maps of growing season NDVI and precipitation were calculated for each year from the period 1985-2000. Our calculations resulted in rainfall-NDVI correlations ranging from 0.45 to 0.91 with a mean value for all years of 0.77. The consistently high correlations indicate a strong association between rainfall and NDVI averaged over growing season, although there is some significant inter-annual variation in the magnitude of the correlation coefficients (Figure 3).

When average growing season NDVI was compared with precipitation summed over the current year and a number of preceding years, values of the correlation coefficient were the highest with precipitation accumulated over 1 current and 2 preceding years (R = 0.88).

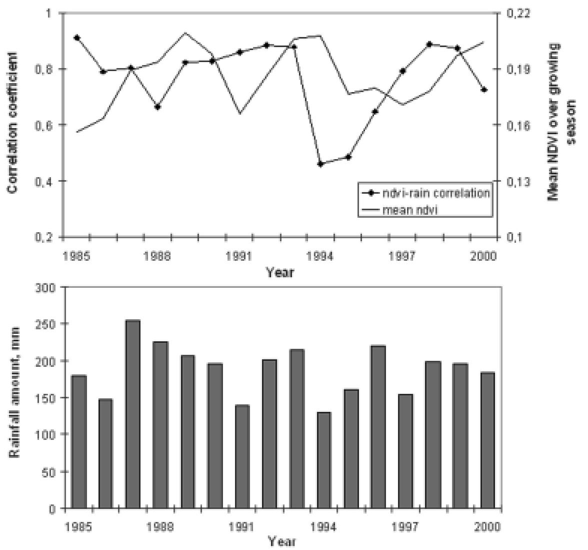


Figure 3. Dynamics of correlation coefficient between NDVI and precipitation versus NDVI value (upper graph); and Evolution of total precipitation amount during 1985-2000 (lower graph).

Stratification of NDVI-rainfall relationships by vegetation type

In order to investigate the influence of vegetation type on the seasonal NDVI-precipitation correlation coefficient, a statistical analysis was performed on three natural vegetation types. Figure 4 shows the results. With regard to vegetation type, the results indicate that correlation coefficient values increase as one moves from desert to semi-desert and to steppe, with R^2 values of 0.36, 0.60, and 0.66, respectively.

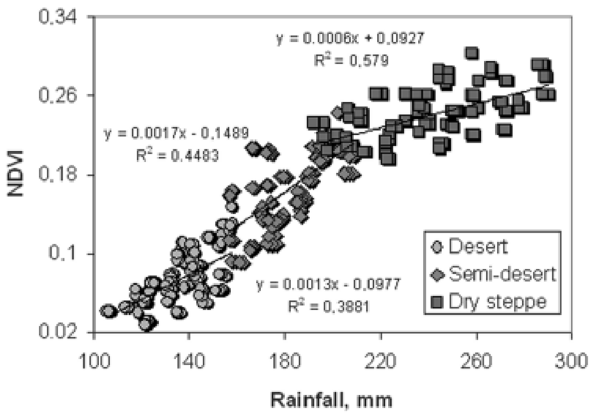


Figure 4. Linear regression between long-time averages of growing season rainfall and growing season NDVI for the vegetation types distributed in the study area.

Saturation point of vegetation response to precipitation

In order to proof, whether there is a saturation limit of precipitation above that the NDVI response decreases, we plotted the values of NDVI-rainfall correlation coefficient against average growing season rainfall (Figure 5). The data presented in Figure 5 indicate that there is a relationship between the NDVI-precipitation correlation coefficient and growing season rainfall. In particular, the coefficient increases as rainfall increases when rainfall is below 220-240 mm. Further; increases in rainfall beyond this level are associated with decreases in the NDVI-precipitation correlation coefficient. However, this threshold is much lower than the saturation limit of 700-800 mm reported for Botswana [18] or 450-500 mm reported for China [13].

Within-season relations between NDVI and rainfall

Within-season NDVI-rainfall correlation coefficients

At the within-season scale, we compared 10-day maps of NDVI with corresponding maps of precipitation. We also incorporated in the correlation analyses various time lags. Spatial relations between NDVI and precipitation were different at every decade of the growing season (Figures 6). Correlation coefficients were generally small in April, increased rapidly in May when the NDVI increased, and achieved in the third decade their maximum. Generally, correlation coefficients slowly decreased during June and after that increased in July, fluctuating only slightly and then decreased in August and September. In the first and second decades of October correlation coefficients reached their maximum values followed by an abrupt decrease in the third decade. In wet years, correlation coefficients permanently increased from April to first decade of September and then dropped off during last five decades of growing season. On the contrary, in dry years, correlation coefficients reached the maximum values in first and second decades of June and then decreased (with high oscillations) until October.

Time lags (from one to five decade period lags) between rainfall and NDVI values had only a weak influence on decadal correlation coefficients in years with dry and normal rainfall values and a higher influence in wet years. Generally, correlation coefficients were worse with time lags of two or three decades in May, September and October, while them improved in June, July and August.

Influence of precipitation amount on NDVI-rainfall relations

In order to understand whether there are any statistically significant relations between the response of vegetation to precipitation and precipitation amounts, the NDVI-rainfall correlation coefficients were plotted against rainfall amounts. These scatter plots are presented in Figures 7. We found a non-linear relationship between 10-day NDVI-rainfall correlation coefficients and 10-day rainfall amounts in all years with exception of the years 1985, 1990, 1997.In general, the correlation coefficients increased as long as the 10-day rainfall does not exceed a definite value. Above this limit, the response of vegetation to precipitation saturates and the NDVI-rainfall correlation coefficient decreases. The limits, above which the NDVI-rainfall correlation coefficients begin to decrease, are different for dry and wet years. In dry years, the saturation limit amount to 12-14 mm of 10-day rainfall. In wet years, this limit is higher, approximately 28-32 mm.

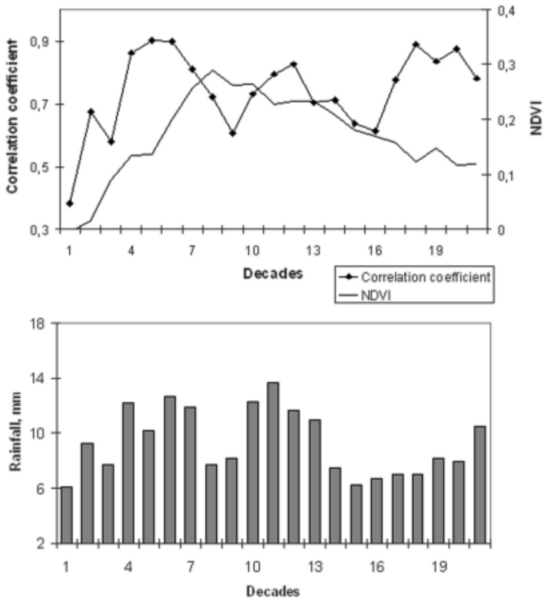
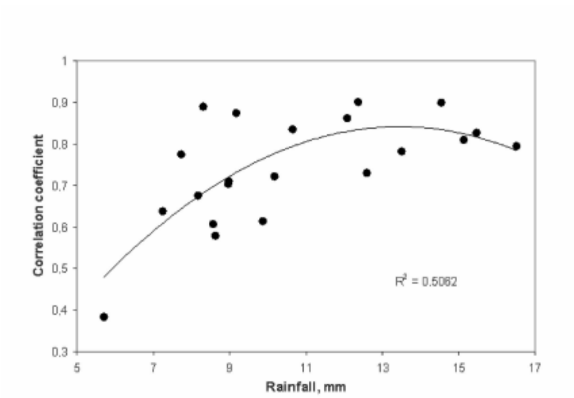
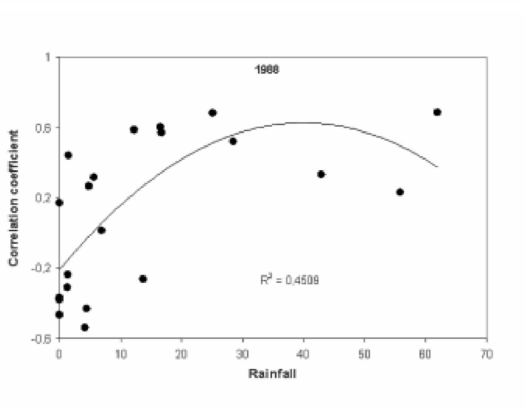


Figure 6. NDVI values, correlation coefficients between spatial distribution of 10-day NDVI and precipitation (upper diagram) and 10-day rainfall (lower diagram).



(a)



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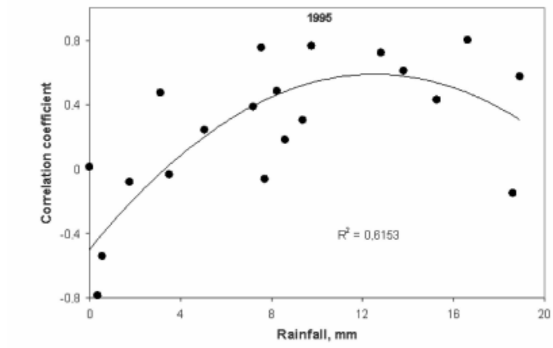

(c)

Figure 7. Scatter-plot of 10-day NDVI-rainfall correlation coefficients versus 10-day precipitation for: (a) average over the study period, (b) the wet year 1988, (c) the dry year 1995.

DISCUSSION

The results of the analyses of NDVI-precipitation relationships at the seasonal scale demonstrated that the correlation is high for all the vegetation categories. This indicates the strong control rainfall has as a limiting factor on NDVI (or vegetation production) in the study region. There were discrepancies in the value of the correlation coefficient between the vegetation categories. Particularly high values were obtained for the steppe region. This seems to be best explained by the diversity that exists between the different dominant vegetation species associated with each vegetation type. These findings correspond to the results of previous studies reported about differences in vegetation respond to precipitation due to vegetation type [6, 13, 18]. We suggested that fractional vegetation cover substantively influences the strength of NDVI-rainfall response in dry lands: thicker vegetation cover produces stronger correlation. Although water is the most important limiting factor in plant growth for desert zone, the relatively weak correlation between NDVI and rainfall obtained for the desert vegetation cannot surprise. In desert areas, supplement of rainfall water in the soils for plant growth is highly depended on the local infiltration ability of soils. Sparse vegetation cover and soil crust strongly influence distribution of fallen precipitation water and allow flowing it far away from the place of its fall. This results in a lower NDVI-rainfall correlation coefficient. As the vegetation cover increases, plant growth and aboveground biomass begins to depend more on rainfall. This is remarkable in the dry steppe land cover category. In steppe areas, where vegetation cover is dense, there is no flash precipitation events and overland runoff. Rainwater keeps supplying at the place of precipitation. Only areas with degrading grass cover create conditions for sheet erosion and overland runoff. These areas show a weaker dependence of vegetation growth on rainfall.

The response of vegetation to precipitation showed significant variance at both the seasonal and within-season scales. This variance seems to be linked to variance in the precipitation amount. The results demonstrated strong association between the strength of the NDVI-precipitation relationship and the amount of precipitation. In general, higher precipitation values caused higher correlation coefficients for both the within-season and seasonal analyses. However, when the precipitation amount reaches values of 220-240 mm per year, the correlation coefficient grows at a slower rate and beyond these values it decreases. The result about existence of the saturation limit in the vegetation response to precipitation is in agreement with the research results obtained by [18] for the Botswana region in Africa and by [13] for China, even though, the thresholds values found in the present study are much lower than in the both above studies. The present study also determined the saturation limit in the NDVI-precipitation relationship for the within-season relationships. When analysing the data aggregated over the whole study region, the NDVI-precipitation correlation saturates at 15-20 mm precipitation per 10-day. This threshold value corresponds in general to the result by [18] (50-100 mm per month).

We suggest that the phenomenon of the saturation in the NDVI-precipitation relationship has a very complicated nature and should be considered in regard to the soil characteristics associated with each individual vegetation type. For plants growing in the study region precipitation events serve as the primary source of water for growth. NDVI values, therefore, are highly correlated with rainfall amounts as long as soil has a capacity to adsorb all rainfall water fallen at the place of precipitation. The infiltration rate of soils in desert, semi-desert and dry steppe zones is limited because of hart crust often build up at the soil surface in dry lands regions. It causes splash effect and enforces water getting away from the place of precipitation event, resulting in a decrease of the NDVI-precipitation correlation coefficient.

CONCLUSIONS

In this paper, spatial distribution of vegetation associated with precipitation patterns has been studied using correlation analysis at seasonal and within-season time-scales. Sensitivity of vegetation cover to inter-annual changes of climatic conditions has also been investigated. The results of our study indicate:

1. There are strong association between spatial patterns of NDVI and that of rainfall in the study area. The average growing season NDVI and 10-day NDVI values are significantly correlated with the corresponding rainfall patterns.
2. The NDVI-precipitation correlation differs clearly between vegetation types. Among the vegetation types studied, desert vegetation shows the weakest NDVI-rainfall correlation. Steppe vegetation shows the strongest relationship between NDVI and rainfall.
3. NDVI-rainfall relationships demonstrate substantial temporal variance. The values of the correlation coefficient vary at the inter-annual scale from year to year and within the single growing season. The within-seasonal variance is somewhat higher than the inter-annual variance.
4. The results revealed that the response of NDVI to rainfall in the study region is not linear. For rainfall levels below 220-240 per year, the NDVI-precipitation correlation coefficient was found to increase with increases in growing season rainfall, reaching a maximum when growing season rainfall was between 220 and 240 mm. Further, rainfall increases beyond these thresholds per year were associated with decreases in the NDVI-precipitation correlation coefficient. For the within-season correlation between NDVI and precipitation, we found a linear relationship as long as rainfall does not exceed approximately 15 mm/10 days. Above this limit, the response of vegetation to precipitation saturates, and NDVI increases with rainfall at a slower rate.
5. 10-day satellite-derived NDVI and precipitation data were used in this preliminary study. In order to investigate thoroughly relationships between NDVI and eco-climatic factors, it was necessary to perform further studies using different temporal and spatial resolutions and additional eco-climatic parameters including soil type, soil temperature and potential evapo-transpiration, etc.

In general, the work has clearly demonstrated that NDVI is a very sensitive indicator for the spatial variability of precipitation conditions at inter-seasonal and within-seasonal time-scales. The results of this study have contributed to a better understanding of the inter-annual and inter-seasonal relations between drylands vegetation and eco-climatic variables in an internal region of Eurasia. The strong relationships between NDVI and precipitation, along with detailed characterization of spatial patterns for our study area, provide the basis for prediction of productivity for various vegetation types under different climate regimes.

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