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MODIS vegetation and water indices for drought assessment in semi-arid ecosystems of Iran

Parinaz RAHIMZADEH BAJGIRAN, Yo SHIMIZU,
Fumiki HOSOI, and Kenji OMASA

(Department of Biological and Environmental Engineering, Graduate School of Agricultural and Life Sciences, The University of Tokyo, 1–1–1 Yayoi, Bunkyo-ku, Tokyo, 113–8657, Japan)

Abstract

In order to evaluate how vegetation indices are affected by climatic patterns and to assess the relationships between them in semi-arid ecosystems of Iran, a six year (2000-2005) time series Moderate Resolution Image Spectrometer (MODIS) data over a six month growing season was used for retrieving Normalized Difference Vegetation Index (NDVI) and two Normalized Difference Infrared Indices (NDII6 and NDII7 using band 6 and 7 MODIS data, respectively) used as Vegetation Water Index (VWI). The study was carried out in dry farming and rangeland areas located in northwestern part of the country. Vegetation indices dynamics and relationships as well as their response to precipitation were studied. The results revealed the high dependence of temporal dynamics of MODIS vegetation indices on precipitation, promising the capability to differentiate drought and normal conditions in different land cover types. Among all indices, NDVI was found to be the best index to be used for drought detection for it had better relationship with precipitation and close relationship with the VWIs. The results of this research can be used as the basis to develop a region-specific drought index for semi-arid regions of Iran.

Key words: Drought, NDVI, Precipitation, Vegetation dynamics, Vegetation water index.

1. Introduction

Arid and semi-arid regions are characterized by low erratic rainfall between 250-500 mm y^{-1}, periodic droughts and different associations of vegetative cover generally short-grass or scrub vegetation. Therefore, these ecosystems are susceptible to rapid land cover change resulting in reduction in productivity and moisture conditions.

Semi-arid regions comprise about 61% of Iran land surfaces having a rainy period generally from November to May followed by a dry period between June and October. Therefore, drought is one of the common natural disasters in the country. According to current literature (Pirdashti *et al*., 2003; Abbaspour and Sabetraftar, 2005) Iran has experienced the driest years during 1999-2001 over the last 50 years. Three consecutive drought years left negative consequences in different parts of the country. Because of the scarcity of meteorological stations and short length of the available data, traditional drought monitoring methods have both temporal and spatial shortages. Since 1980s, using satellite data, many researches have been carried out for detailed drought detection and vegetation phenology and changes studies.

Normalized Difference Vegetation Index (NDVI) using the reflectance of near infrared and red bands is one of the most popular indices used for vegetation monitoring (Tucker *et al*., 1981) and drought detection (Kogan, 1990; Liu and Kogan, 1996; Anyamba and Tucker, 2005). NDVI reflects changes in chlorophyll content and vegetation amount and has proved to be a useful tool for studying vegetation cover change and amount in semi-arid environments. Weiss *et al*. (2004) concluded that NDVI is a good tool for characterizing vegetation variability in arid and semi-arid regions and allows long time-scale analysis of vegetation behavior

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in response to climate variability. Climatic control of the spatial patterns of NDVI has been observed in other semi-arid regions (Malo and Nicholson, 1990; Farrar *et al*., 1994; Liu and Kogan, 1996; Vicente-Serrano *et al*., 2006).

Recently, Vegetation Water Indices (VWIs) using wavelengths around 1240 nm, 1640 nm or 2100 nm in combination with near infrared have been applied as independent vegetation measure for retrieving canopy water contents instead of chlorophyll amount. Because in semi-arid environments, water is usually considered the limiting factor in biomass production, VWIs can provide us with valuable information on vegetation and/or soil water stress and detecting drought status. Gao (1996) introduced the Normalized Difference Water Index (NDWI) using 1240 nm and 860 nm wavelengths to retrieve vegetation water content. Fensholt and Sandholt (2003) developed the Shortwave Infrared Water Stress Index (SIWSI) using 1640 nm and 860 nm wavelengths and found a strong relationship between the index and soil moisture in semi-arid ecosystems of Sahelian zone in Africa. Also studies have shown that the combination of both NDVI and VWIs can provide great information on vegetation phenology and types, water availability and drought (Maki *et al.* 2004).

High-frequency temporal data of MODIS instrument having appropriate water absorption bands for retrieving canopy water contents offer a great opportunity to study regional and global environmental changes. Xiao *et al*. (2005) applied MODIS band 6 (1628-1652 nm) and band 2 (841-876 nm) with NDVI and Enhanced Vegetation Index (EVI) as a surface moisture index to monitor paddy rice agriculture dynamics. Gu *et al*. (2007) presented the strong relationship between MODIS NDVI and NDWI (derived from MODIS band 7 (2105-2155 nm) and band 2) and drought conditions in grasslands in Finit Hills ecoregion-USA. Cheng *et al.* (2008) indicated the capability of MODIS NDWI and NDII (Normalized Difference Infrared Index) using MODIS band 2 and 6 for estimation of canopy water content in a semi-arid site in Arizona.

Although the application of vegetation indices such as NDVI and VWIs has proved to be a great tool for detecting vegetation amount, soil/vegetation water content and drought, due to the complexity of each ecosystem, relationship between vegetation activity and water content in various land cover types in relation to climate variation is different and must be studied. Long term analysis of the vegetation indices over wet, normal and dry years is an indispensable requirement to provide better insight into vegetation response to climate variations. In Iran, very limited studies have focused on the evaluation of climate effects on ecosystem and drought detection using remotely sensed data. To the best knowledge of the authors, no literature on the application of VWIs in Iran is available. The present research is the first attempt to develop six year time series MODIS data and analysis of NDVI and VWIs in the ecosystems of Iran. The objectives of this research were to study: 1) the NDVI and two Vegetation Water Indices (using band 6 (NDII6) and band 7 (NDII7)) inter and intra growing season temporal variations in the semi-arid dry farming and rangeland areas located in northwestern part of Iran, 2) the relationship between NDVI and each VWI in studied land cover types and 3) the response of vegetation indices to precipitation as the main climatic variable to evaluate their capability to be used as a tool for drought detection. This information will be of high significance to study the vegetation dynamics and understand the relationships between these vegetation and water indices and/or precipitation in semi-arid regions such as Iran where climatic and field data for vegetation condition monitoring are highly limited.

2. Materials and Methods

2.1 Data and methodology

MODIS-Terra 8-day 500-meter atmospheric corrected reflectance products (MOD09A1) for six years (2000 through 2005) April through September (6 months in growing season) were obtained for the purpose of this research. The images were composites generally located in the middle of each month and were labeled by their DOY starting from the first day of each 8 day period. Cloud pixels and fill value pixels were masked out using MODIS quality flags data. Then NDVI and VWIs (NDII6 and NDII7) were calculated for the entire study area from April to September 2000-2005 to investigate temporal variation of vegetation indices during growing season and during dry to wet years and in relation to inter and intra annual rainfall using the following equations:

$$\mathrm{NDVI} = (\rho_{NIR} - \rho_{RED}) / (\rho_{NIR} + \rho_{RED}) \quad (1)$$

$$\mathrm{NDII6},\ \mathrm{NDII7} = (\rho_{NIR} - \rho_{SWIR}) / (\rho_{NIR} + \rho_{SWIR}) \quad (2)$$

where ρ_{NIR} and ρ_{RED} are the surface reflectance values of MODIS band 2 (841-876 nm) and band 1 (620-670 nm), respectively, ρ_{SWIR} is the surface reflectance value of MODIS band 6 (1628-1652 nm) for NDII6 or band 7 (2105-2155 nm) for NDII7.

Also daily and monthly precipitation data for 30 meteorological stations (supplied by Iran Meteorological Organization and Water Resources Research Organization (TAMAB)) in the study area, covering the years 2000-2005 were collected. For the purpose of this research, weekly and monthly precipitation maps for all six years were produced using Inverse Distance Weighted (IDW) interpolation method. Precipitation maps were produced using concurrent rainfall data, the week before the composite image date, cumulative two-week, cumulative three-week, and cumulative one-month, two-month and three-month data.

Three different land cover types were selected using the National Plan for Land Use Map of Iran vector map (Ministry of Agriculture, 2005) and field survey. Pixel values for these three land cover types including dry farming (350 km^2), plain rangeland (250 km^2) and mountainous rangeland (rangeland and shrubs) (200 km^2) were extracted from NDVI, NDII6, NDII7 and precipitation maps for the entire six year period.

2.2 Study area

The study area in this research covers parts of semi-arid regions of northwestern Iran located in Zanjan province. This region has cold semi-arid climate with 330 mm average annual precipitation. Mean annual temperature is 11℃ with the mean maximum and minimum of 18 and 4.5℃, respectively. Rainy period is generally from November to May whereas there is rare to almost no precipitation from July to September. Around 50 percent of the total precipitation falls during March to May. The dominant land cover types in the study area are plain rangeland, mountainous rangeland, dry farming, scattered dry farming and irrigated farming along rivers, respectively. For the purpose of this research, three land cover types including dry farming areas, plain rangeland and mountainous rangeland were analyzed. The dry farming land cover was dominated by wheat and barley fields. The plain rangeland was located at 1400-1700 m elevation having mostly annuals and perennial short grasses including *Agropyron spp.*, *Brumus spp.*, *Stipa sp.*, *Holtemia persica.*, *Artemisia sp.*, and *Astragalus sp.* The mountainous rangeland comprised both grasses including *Festuca spp.*, *Stipa spp.*, *Brumus spp.*, *Astragalus spp.*, and woody shrubs including *Juniperus excelsa*, *Crataegus spp.*, *Amygdalus spp.*, and *Cotoneaster sp.* at higher elevations (1900-2200 m). The location of the case study area is shown in Fig. 1. Plain rangeland and mountainous rangeland information is not differentiated in this figure because this information was not included in the used vector map. These two rangeland types were separated according to the field survey conducted in August 2008 and also available topographic maps of the study area.

3. Results and Discussion

3.1 Inter and intra annual vegetation dynamics

In this part, vegetation amount and land canopy water condition anomalies during six month growing season in six years were studied. Fig. 2 presents NDVI, NDII6 and NDII7 dynamics over the entire

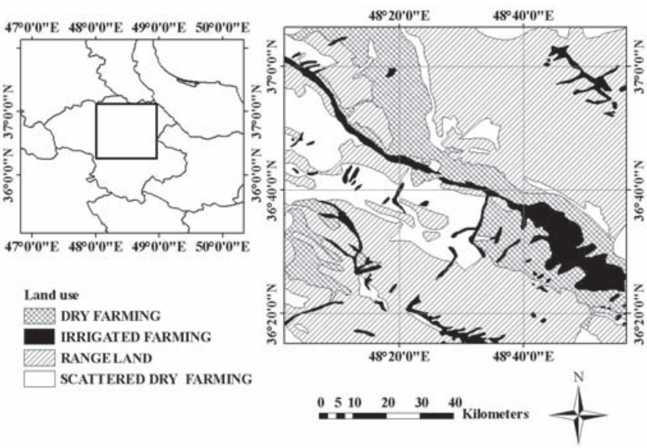

Fig. 1. Location of the study area.

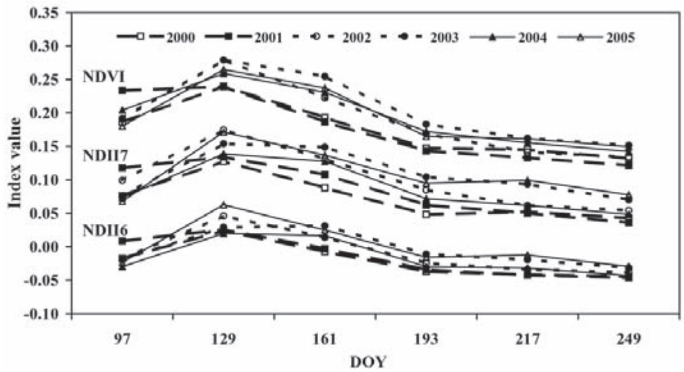

Fig. 2. NDVI, NDII6 and NDII7 dynamics over the entire study period averaged for all vegetation cover types (DOY indicates the beginning of the 8 day period as it is originally labeled by MODIS).

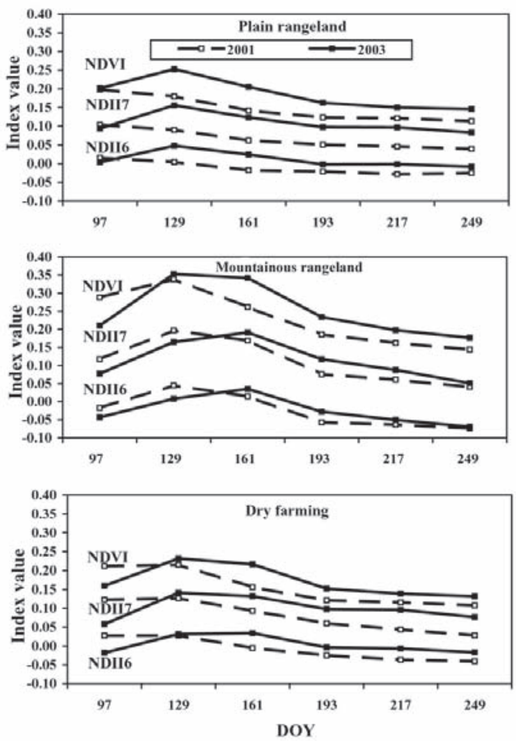

Fig. 3. Comparison of vegetation indices in dry year (2001) and wet year (2003) in the dry farming, plain rangeland and mountainous rangeland.

study period averaged for all vegetation cover types. All indices exhibited similar time-series inter-annual and intra-annual patterns. Similar observations have been made elsewhere (Cheng *et al*., 2008; Gu *et al*., 2007). In all cases, increases in vegetation indices from April to May (DOY 97-129), followed by decreases from June to September (DOY 161-249) can be easily observed. From this figure, years 2000 and 2001 can be identified as the driest years whereas the years 2002-2005 had better water availability. Meteorological data and research literatures confirm the occurrence of droughts in years 2000 and 2001 (Pirdashti *et al*., 2003; Abbaspour and Sabetraftar, 2005).

In order to provide better comparison between vegetation indices in drought and normal years in each land cover type, only vegetation indices anomaly during 2001 (a drought year) and 2003 (a wet year) are presented in Fig. 3 for each land cover separately. Mountainous rangeland generally exhibits the highest NDVI value as compared with two other land cover types. This can be attributed to the denser vegetation cover (both range and woody species) and less degradation due to the human activity. The plain rangeland is degraded and overgrazed whereas the dry farming has rotations in a scattered manner. All vegetation indices show lower values in 2001 in all three land cover types except at DOY 97. In this year, the mean annual precipitation in the study area was 205 mm in comparison with 380 mm in 2003 (normal precipitation 340 mm). Therefore in 2001, reduction in precipitation was around 40 percent. Comparing different land cover types, some differences in the anomaly patterns between the wet and the dry year can be easily distinguished. In all land cover types almost all indices reach their maximum between May and June (DOY 129-161) in the wet year whereas in dry year the patterns are different among different land covers. In mountainous rangeland, the trends for the dry and wet years are more or less the same. However in plain rangeland and dry farming land covers, the peaks in May and June are not observed. The fact

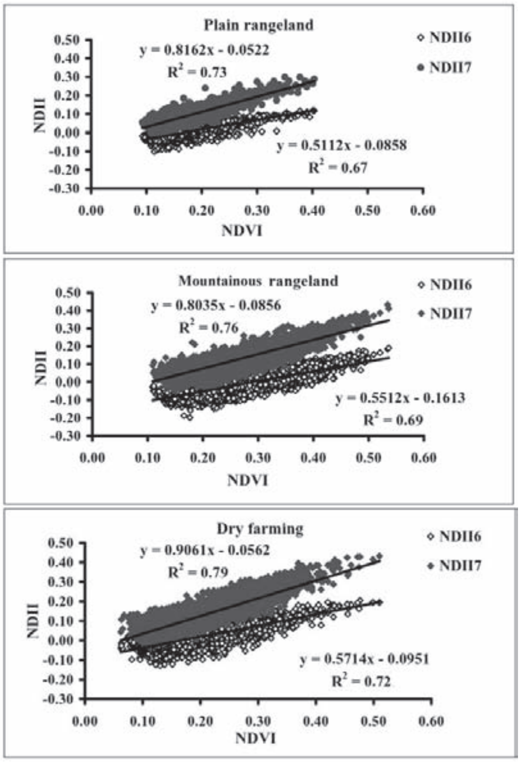

Fig. 4. Relationships between NDVI and VWIs during six years for the three land cover types.

that perennials and woody species in high lands are less susceptible to dry conditions can explain this observation. In addition, calculating the changes in index values in percents in the dry year as compared with the values in the wet year, it is observed that in the drought year, VWI values decreased more than NDVI values especially during summer time (DOY 193-249 in Fig. 3). For example, summer time NDVI values for all three land cover types decreased similarly around 20 percent whereas NDII7 values for dry farming and plain rangeland decreased around 50 percent and that of mountainous rangeland around 30 percent. This shows that NDII7 might be more sensitive to drought conditions than NDVI (Gu *et al*., 2007).

3.2 Relationship between NDVI and VWIs

This part of the study deals with the evaluation of the relationships between NDVI and VWIs. These relationships during six years for individual pixels for the three studied land cover types are presented in Fig. 4. Chlorophyll amount (as depicted by NDVI) and vegetation water content (as depicted by VWIs) were found to be strongly related. In all cases, the relationships between NDII7 and NDVI were both more significant and steeper than those between NDII6 and NDVI. This means that NDII7 is more influenced by vegetation amount than NDII6 and will probably be a better index than NDII6 to reflect vegetation water content in semi-arid regions. Among different land cover types, dry farming (R^2: 0.79), mountainous rangeland (R^2: 0.76) and plain rangeland (R^2: 0.73) exhibited the highest coefficients of determination, respectively. The coefficient of determination was the best in dry farming. This can be attributed to the fact that dry farming land cover is more uniform in terms of vegetation species variability.

An interesting point observed in Fig. 4 is that the dependence of vegetation water index on NDVI (seen as the slope of the regression line) is different in the three land cover types. The highest slope is seen in dry farming followed by plain rangeland and mountainous rangeland, respectively. While the difference in slope between the two rangeland types is negligible, the higher slope in the case of dry farming is considerable.

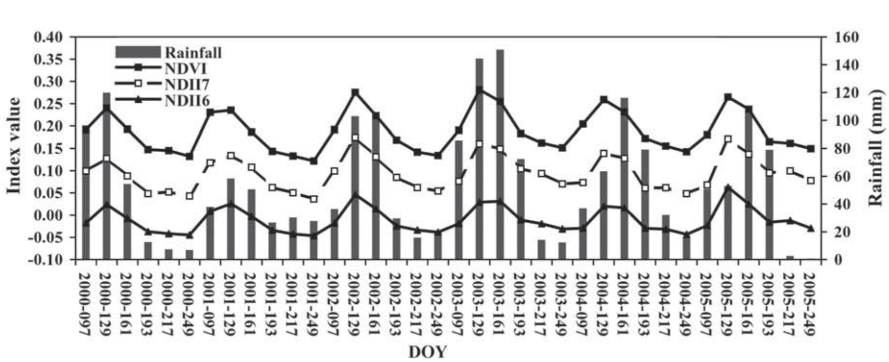

Fig. 5. Anomaly of the three indices and two-month cumulative precipitation averaged for all land cover types.

Huete (2005) reported higher slope and coefficient of determination between MODIS EVI and NDII7 in degraded open forests as compared with protected areas. It can be suggested that in the present study, human induced land cover manipulation can have a similar effect on the relationship between vegetation amount and water content.

3.3 Relationship of NDVI and VWIs with rainfall

In this part, different precipitation scheme maps (as defined under Materials and Methods) were produced to study the VWIs and NDVI response to rainfall in all land cover types in the study area. We expected differences between NDVI/VWIs and rainfall relationships and also in each land cover type. As VWIs are expected to reflect both vegetation and soil water contents, it could be expected that these indices be affected by more recent precipitation events. However, such an observation was not made in the present study indicating that both NDVI and VWIs are influenced similarly by longer term precipitations. Among all precipitation schemes, monthly and two-month cumulative precipitation patterns had better relationships with vegetation indices where two-month cumulative precipitation was found to have the best relationship with vegetation indices. Little work has been done on the relationships between VWIs and precipitation in semi-arid environments. However, the results of the present study are in agreement with the available data (Cheng *et al.* 2008). Previous studies on NDVI had shown that in arid and semi-arid regions with dry months during growing season, it is the cumulative precipitation which determines vegetation condition especially during summer (Vicente-serano *et al.*, 2006; Rahimzadeh Bajgiran *et al.*, 2008).

Fig. 5 presents the anomaly of the three indices and two-month cumulative precipitation averaged for all land cover types. Generally the trends of NDVI and VWIs are similar to that of precipitation indicating that the vegetation condition is strongly dependent on cumulative precipitation. Over the years 2000 to 2003, peaks of precipitation and those of the indices coincide whereas in years 2004 and 2005, they do not. This is partly due to the distribution of rainfall over the entire growing season. As reported earlier, precipitation in late growing season has been unable to induce changes in vegetation condition (Rahimzadeh Bajgiran *et al.*, 2008).

Table 1. Coefficients of determination (R^2) between NDVI, NDII6 and NDII7 and two-month cumulative precipitation.

Land use	NDVI	NDII7	NDII6
Mountainous rangeland	0.65	0.60	0.55
Plain rangeland	0.48	0.38	0.39
Dry farming	0.53	0.37	0.41

Coefficients of determination between NDVI, NDII6 and NDII7 and two-month cumulative precipitation are presented in Table 1. MODIS NDVI, NDII7 and NDII6 from mountainous rangeland showed good correlation with two-month cumulative precipitation (R^2: 0.65, 0.60 and 0.55, respectively). For dry farming and plain rangeland, pretty good correlations were obtained between NDVI and two-month cumulative precipitation. On the contrary, the relationship between NDII7 and NDII6 and precipitation was not very good in both dry farming and plain rangeland. This can be attributed to the lack of response to summer precipitation and possible disturbance by human activities.

As clearly seen, NDVI values exhibited higher R^2 values with precipitation than those of NDII7 or NDII6 in all land cover types and also in entire study area, indicating that this index is a better indicator of drought conditions. NDII7 and NDII6 have shown almost similar relationships with two-month cumulative precipitation in all land cover types. All correlations have been found to be statistically significant at 1% error regardless of their coefficients of determination values.

4. Conclusion

The six year evaluation of the study area using MODIS NDVI and VWIs showed that temporal dynamics of vegetation was highly dependent on precipitation so that it is possible to distinguish drought conditions from normal ones in different land cover types. Strong relationships found between NDVI and VWIs (especially NDII7) suggest that vegetation water content is highly dependent on vegetation amount. Also between vegetation indices, NDVI had better relationship with precipitation in all land cover types. Therefore, should only one index be opted for drought detection in the study area, it would be NDVI because of the better relationship between precipitation and close relationship with the VWIs. However, considering the different nature of the information provided by NDVI and VWIs, information from VWIs should not be overlooked. In general, temporal response of

MODIS vegetation indices to precipitation suggests the potential of these data for long term environmental monitoring and changes in semi-arid regions of Iran.

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