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RESEARCH PAPER

Assessment of agricultural drought using MODIS derived FAO's agriculture stress index system (ASIS) over the Iran croplands

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Abstract
In Iran, the drought is one of the costliest natural disasters, which has devastating consequences for the food security of agricultural households. Drought monitoring characteristics are important for better understanding of the drought phases in mitigation planning. Various satellite-based drought indices and systems have been developed and applied at both the regional and global scales. Recently the remotely sensed agricultural stress index system (ASIS) based on imagery from the Advanced Very High Resolution Radiometer (AVHRR-NOAA) and Meteorological Operational Satellite (METOP) by the Global Information and Early Warning System (GIEWS) of FAO developed. It shows considerable potential for drought monitoring at the global scale. Vegetation Health Index (VHI), start and end of the crop season (SOS-EOS) are the main inputs of ASIS. While the GIEWS models use the METOP-AVHRR images (1984 at present), in this study, an attempt has been made to retrieve key ASI inputs from the Moderate Resolution Imaging Spectroradiometer (MODIS) to evaluate the ability of the MODIS ASIS for characterizing agricultural drought severity and explore the impacts of drought on crop production during growing season.
Comparing national and sub-national wheat and barley yields with the ASIS drought maps, demonstrated that the proposed approach could identify major historical droughts over the observed period (2002-2015) in Iran. We detected that the extreme severe drought occurred during the year 2007-2008 crop season, affecting approximately 64% of crop land.

Keywords: Agricultural Stress Index, Iran, Agricultural Drought, MODIS, Crop coefficient, Vegetation health index.

Introduction

Iran located primarily in semiarid regions, has been suffered from a water resource scarcity, and persistent drought (Karamidehkordi, 2010; Zoljoodi and Didevarasl, 2013; Golian *et al.*, 2015; Madani et al., 2016).

While agriculture sector is often the first and most vulnerable sector to be affected by drought events (Qu, 2015), producing crop failure and water scarcity that threat the sustainability of food security in the country. Drought is one of the nation's most costly natural disasters in Iran (Zarafshani *et al.*, 2012). In 2001, Iran experienced extensive drought which affected approximately 8 million hectares of country’s agricultural lands and the total agricultural and livestock losses by the year 2001 were estimated to be US$ 2.6 billion (Morid *et al.*, 2006). Identification of the onset, extent, intensity and duration of drought during a crop cycle is crucial to implement programs that aim to increase food security and mitigate the drought impacts (Qu, 2015).

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To quantify drought and monitor its development, various satellite-based drought indices and systems have been developed and applied, such as Normalized Difference Vegetation Index (NDVI) (Rouse *et al.*, 1974), the Vegetation Condition Index (VCI) (Kogan,1995), the Temperature Condition Index (TCI) (Kogan,1995), and the Vegetation Health Index (VHI) (Kogan, 1995) to name a few.

VHI considers VCI and TCI within a period of observation; both parameters are derived from NDVI and LST data. VHI as a weighted combination of VCI and TCI, which characterizes moisture and thermal conditions and the vegetation health. VHI has been widely used to monitor agricultural areas affected by drought at regional and local scales in several parts of the world (Kogan, 2002; Singh *et al*., 2003; Salazar *et al*., 2007; Seiler *et al*., 2007; Rojas *et al*., 2011).

Rojas *et al*. (2011) developed Agriculture Stress Index (ASI) using a combination of historical time series of VHI images at 16 km resolution derived from NOAA-AVHHR, phenology maps, and ancillary data across the whole African continent. The developed methodology represents the percentage of agricultural areas within each administrative region affected by drought over the growing season. ASI proved to be a valid drought indicator for the African continent and it was highly correlated with the drought events recorded during the period (1981-2009) (Rojas *et al*., 2011).

The Global Information and Early Warning System (GIEWS) of the Food and Agriculture Organization of the United Nations (FAO), improves ASI methodology to allow drought assessment in near-real time (NRT) and at global scale (Hoolst *et al*., 2016).

In order to investigate the agriculture drought in Iran within the past two decades, we use FAO's ASI Approach to detect temporal and spatial patterns of agricultural stress derived by earth observation data at the country level.

Within this study, Moderate-resolution Imaging Spectro-radiometer (MODIS) NDVI and LST time series from 2002 to 2015 were investigated. The aim of the study was to reveal the drought characteristics (strength, variability, and patterns) in Iran.

Cereal crops (i.e. wheat, barley, and rice) cover almost 70% of the cultivated land, while wheat alone covers nearly 70% of the aggregate cereal production (MAJ, 2015). Annual crop statistics (wheat and barley) has been analyzed to assess the impact of the agricultural drought on the crop production.

Materials and method

Study Area

Iran is a semi-arid country located between 25º-40º N and 45º-65ºE, with a total surface of 1,648,000 km^2. The country has a broad spectrum of climatic conditions across regions with annual precipitation from 0 to 2000 mm and temperatures from −20 to +50ºC (Abbaspour *et al*., 2009).

Based on the 2015`report of Iranian Ministry of Agriculture-Jahad (MAJ, 2015), the long-term (1978–2013) average area under cultivation was about 12 million hectares of which 49% is assigned to the irrigated lands and 51% is assigned to rain-fed lands (MAJ, 2015). Cereal crops (i.e. wheat, barley, and rice) cover almost 70% of the cultivated land, while wheat alone covers nearly 70% of the aggregate cereal production (MAJ, 2015). The major wheat and barley producing provinces of Iran are presented in Figure 1. These selected provinces represent 86.5% and 84.7% of the national wheat and barley production, respectively (Ababaei and Etedali, 2016).

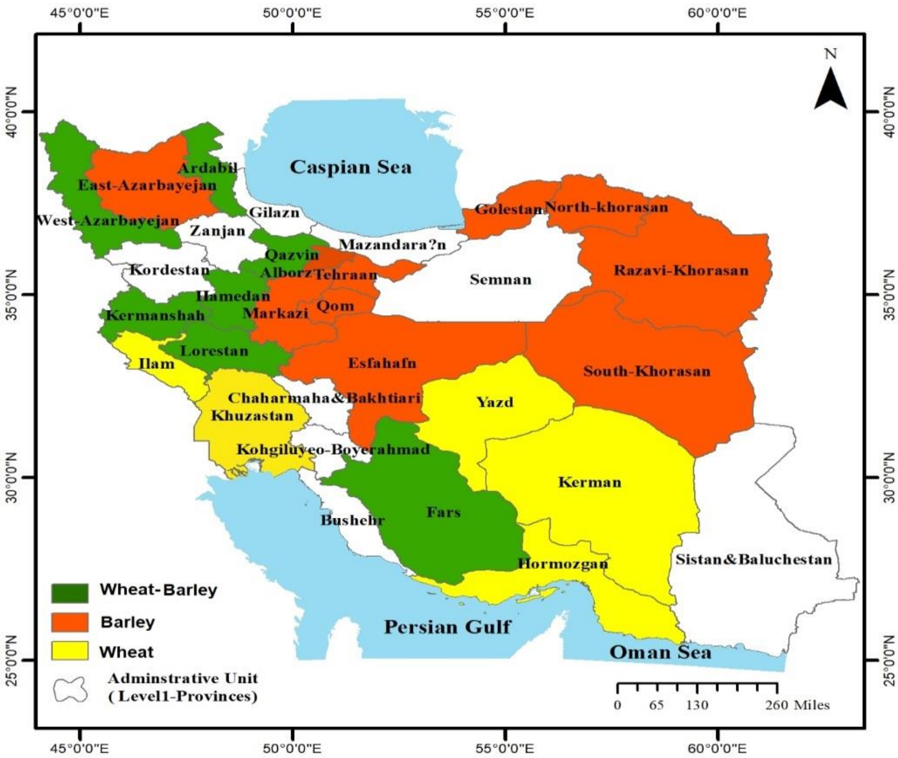

Figure 1. Major wheat and barley producing provinces in Iran

Data

MODIS data

In this study, we used two MODIS land surface products .The first product was the 8-day Terra MODIS Surface Reflectance product (MOD09A1, 500 m, corrected for atmospheric conditions such as gasses, aerosols, and Rayleigh scattering), which was used to drive 8-day NDVI datasets for the years 2000-2015 using near-infrared and red bands. The second product is the MODIS 8-day Land Surface Temperature (LST) (MOD11A2, collection v005, 1 km) was used for the years 2000-2015. MOD11A2 is composed of daytime and night-time LST variables at a time interval of eight days. All MODIS products were processed, re-projected, and converted to the GeoTIFF format using the MODIS Re-projection Tool Version 4.0 (MRT) downloaded from LPAAC (https://lpdaac.usgs.gov/lpdaac/tools). The nearest neighbor resampling algorithm was used to resample MODIS NDVI images to match the 1 km spatial resolution LST datasets.

Crop yield data

Provincial data on agricultural crop production and yield from 2000 to 2015 were obtained from MAJ (2015). We used barley and wheat yields to validate and test the potential use of the ASI.

Crop land extent

The combination of global cropland extent product at 250 m produced using multi-year MODIS NDVI (Pittmanetal., 2010) and Glob Cover Classification (version 2.3, http://due.esrin.esa.int/page_globcover.php), derived by an automatic and regionally-tuned classification of a time series of global 300 m MERIS sensor on board the ENVISAT satellite for the year 2009, were used in this study.

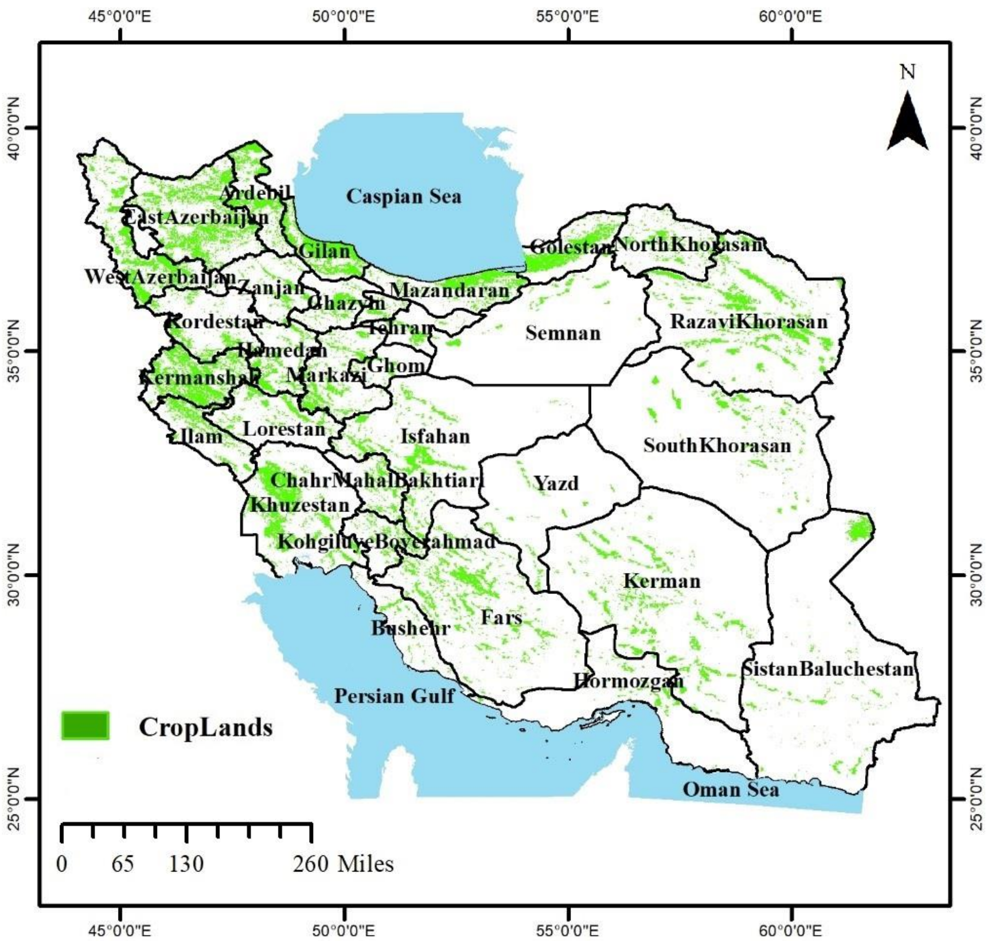

Figure 2. Crop Lands of Iran

Methodology

A schematic overview of the general methodology, including primary inputs and image processing steps, is shown in Fig.3. Following the approach of Kogan (1995), VCI and TCI derived from the time series of LTS and NDVI, respectively (see section 2.2.2). Finally, both anomalies were combined into the VHI.

The local phenology metrics were derived from the long-term NDVI averages over the years 2000-2015 from MOD09A1 (see section 2.2.1). The next step concerned temporal VHI (μVHI) aggregation (see Section 2.2.3). Finally, the percentage of the cropped pixels within each administrative region, with μVHI below a certain threshold (μVHI <0.35) were calculated. Final results could be compared with the ground observation and reports. All spatial data processing and procedures described here were implemented via Python-script in the ArcGIS 10.2 platform.

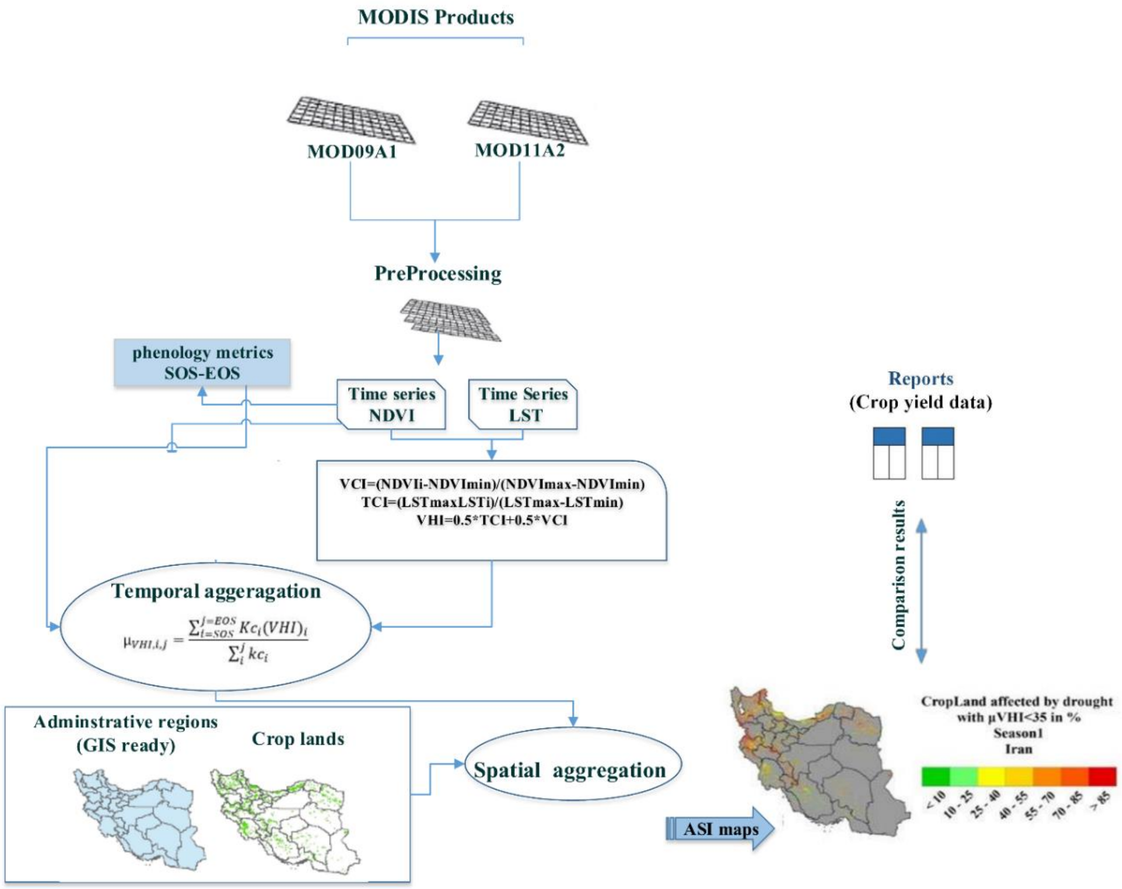

Figure 3. Flow chart of the processes used in this study

Phenological parameters from NDVI data

There are many different approaches to derive SOS and EOS from times series of vegetation indices. NDVI is frequently adopted for the estimation of crop phenological metrics including SOS and EOS from various sensors of ground and satellite platforms (Wu *et al*., 2017) White *et al*. (1997) and Rojas *et al*. (2011) used the 50% threshold method to extract phenological timing from NDVI. SOS is the moment between per year maximum and minimum of NDVI when NDVI reaches the average between maximum and minimum (50% threshold) and EOS is the moment after maximum when the NDVI-curve again reaches the same level (Rojas *et al*., 2011).The mentioned method was modified by Hoolst *et al* (2016), using SOS=0.25 $NDVI_{max}$ and EOS=0.75$NDVI_{max}$ thresholds. In this work, the same way as Hoolst *et al* (2016), used to extract phenological metrics from the NDVI time series (2000-2015) derived from MOD09A1. For consistency in the multi-year analysis, the SOS and EOS-values were averaged for all years and all pixels within a unit. Hoolst *et al*. (2016) described the methods for estimating SOS and EOS data in detail.

Vegetation Health Index (VHI)

VCI, TCI and VHI indices were derived by following equations:

$$VCI = 100 * \frac{(NDVI_a - NDVI_{\min})}{(NDVI_{max} - NDVI_{\min})}$$
(1)

$$TCI = 100 * \frac{(LST_{max} - LST_a)}{(LST_{max} - LST_{\min})}$$
(2)

Where, $NDVI_a$ and LST_a represents NDVI and LST values of current 8-day period, while ($NDVI_{max}$, LST_{max}) and ($NDVI_{min}$, LST_{min}) represent the maximum and minimum NDVI and LST values, of the time-series of observation, respectively. Finally, both anomalies are combined into VHI formula as described below:

$$VHI = 0.5(VCI) + 0.5(TCI)$$
(3)

Temporal VHI aggregation

In this section, the 8-day VHI images between the SOS and EOS were averaged to retrieve temporal VHI aggregation over the growing season. In first stage, using equation 4 (Rojas *et al*. 2011; Hoolst *et al*. 2016) assign equal weight for all VHI images within growing season to retrieve μVHI was assumed.

$$\mu_{VHI,i,j} = \frac{1}{j-i} (\sum_{i=SOS}^{j=EOS} (VHI)_{i,j}$$
(4)

Spatial VHI aggregation

In this section, spatial VHI aggregation was implemented in the same way as described by Rojas *et al*. (2011) and Hoolst *et al*. (2016). In brief, FAO's ASI was calculated as the percentage of cropped pixels, within each administrative region with μVHI below a certain threshold (fixed at μVHI< 0.35). For assessment the extent of drought within a specific region, the results could be compared to ground observation and reports.

Results

Retrieval of the key ASIS inputs (SOS, EOS, and VHI)

Figure 4 represents the phenological metrics, A: start of season (SOS), B: end of season (EOS).

The climate patterns in north, west and southwest differ from central and eastern crops. While the start of the growing season varies between January and March, we see different patterns at the end of the harvest season (Figure 4).

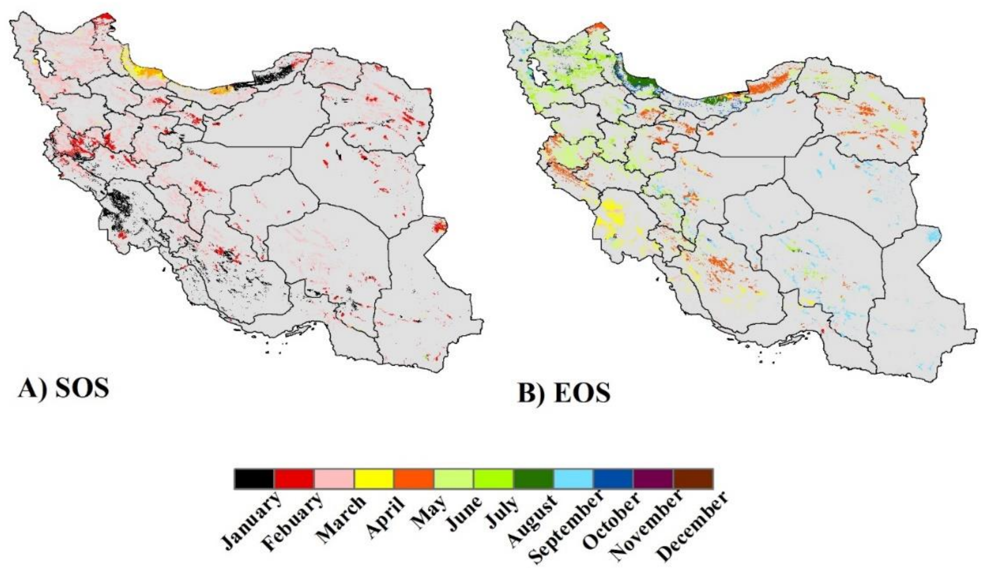

Figure 4. Phenological metrics, A: start of season (SOS), B: end of season (EOS) derived from the time series of NDVI-MODIS images

Figure 5 shows the annual averages of the MODIS VHI images from 2002 to 2015 at a 1 km resolution over the non-desert area of Iran. A decrease in the VHI would, for example, indicate relatively poor vegetation conditions, signifying stressed vegetation conditions, and over a longer period would be indicative of drought. 2008 was reported as one of the driest years with strong impacts on vegetation and great damage to local agriculture.

MODIS based ASI maps

Following the section 2.2 procedures, the spatial distribution of agricultural drought conditions was mapped for the first crop season in the years 2002-2015 at sub-national administrative level in Figure 6.

Analyzing the results of ASI maps based on MODIS for a 14-year period (2002–2015), we detected that the extreme severe drought occurred during the year 2007-2008, affecting approximately 64% of the crop land (Figure 6). According to 2008 MODIS-ASI map result, the drought appears to be affecting the majority of the agricultural areas, including the west, northwest, center and northeast of Iran.

Discussion

The results of ASI maps in 2008 were consistent with the precipitation observations reported by Iran Meteorological Organization which found that drier-than-normal conditions in all four seasons (Spring-Summer-Fall-Winter) of 2008, caused a severe drought (Khoshkam and Rahimzadeh, 2009), consequently leading to the issues of food security. On the basis of reports by MAJ (2015), 50% of agricultural lands were affected by drought and harvested area of rain-fed and irrigated declined 50 and 45% from the previous year, respectively. A US$ 19 billion loss in the agricultural division has been also reported during 2006 to 2008 (Modarres *et al*., 2009).

Based on Khoshkam and Rahimzadeh's (2009) report, areas with above-average winter rainfall were confined to the southeast and small parts over the northwest, while the rest of the country received precipitation amounts that were at most 75% of the long-term mean.

Based on 2008 MODIS-ASI map result, the crop lands of Sistan and Baluchestan, located in the southeast of country, were less affected during drought. Northwest and west were the worst-affected areas including East Azerbaijan, West Azerbaijan, Chaharmahal and Bakhtiari, Zanjan, Kordestan, Lorestan, Kohgiluyeh and Boyer-Ahmad, Ilam and Kermanshah provinces where crops (especially wheat and barley) are mainly rain-fed.

The percentage of Iran's crop land affected by drought based on MODIS ASI result, and crop's yields change for each crop season (from 2002 to 2015) has been plotted in Figure 7. Iran's agricultural drought conditions closely conformed with the yield reduction percentage over the crop seasons (Figure 7).

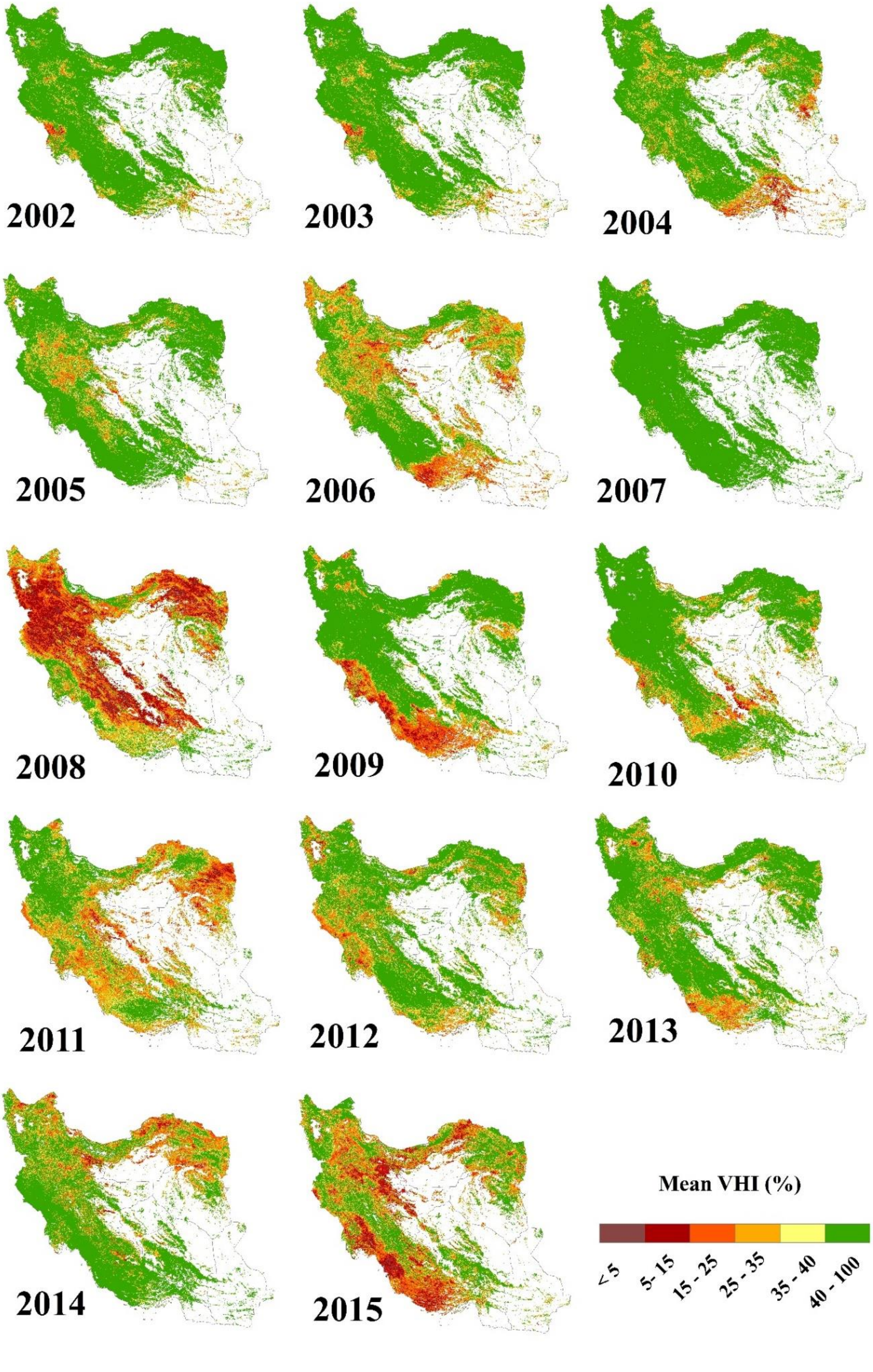

Figure 5. Spatial distribution for mean VHI, based on the original classification scheme during the growing seasons from 2002 to 2015. The water, wetland and desert regions are masked

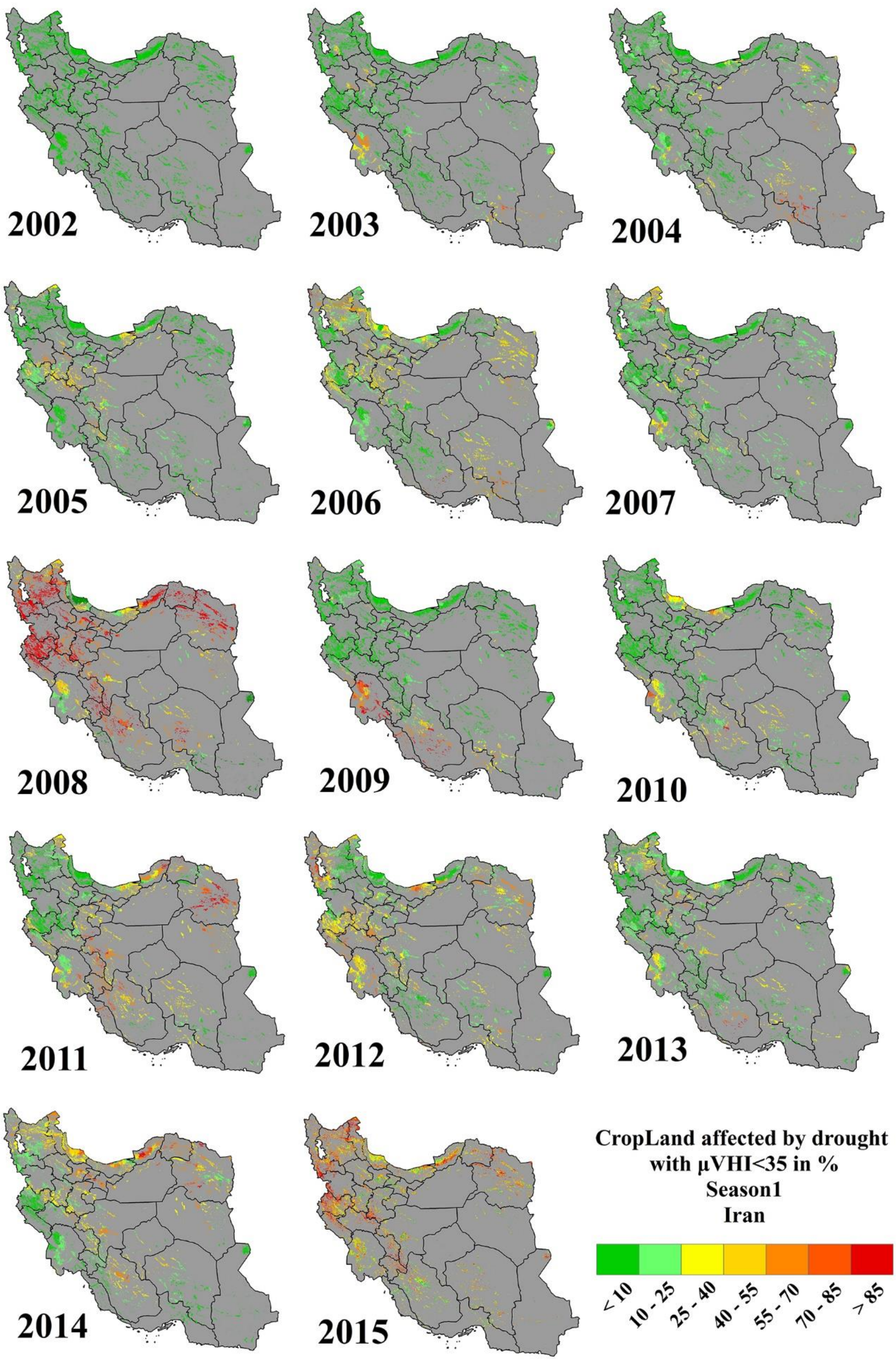

Figure 6. Percentage of agricultural area affected by drought during the first crop season (VHI < 35%) from 2002 to 2015

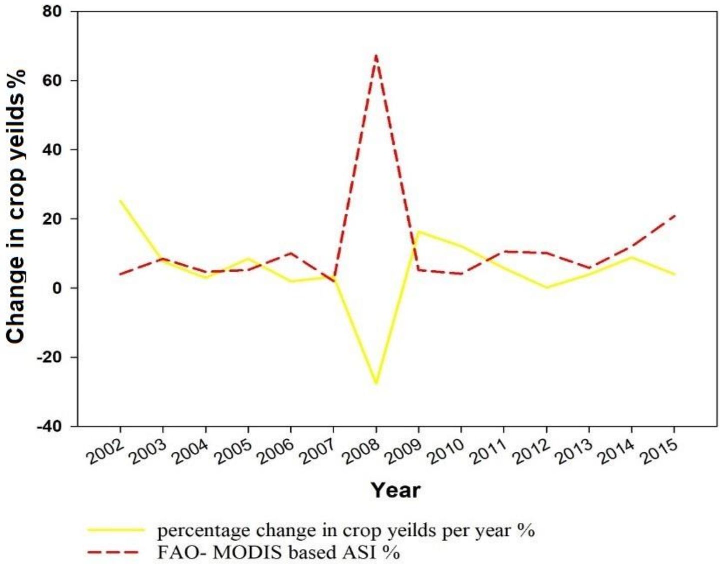

Figure 7. The percentage of the crop land affected by drought using MODIS ASI and crop yields change from 2002 to 2015

For example, the obtained results by ASI showed that 67.21% of the crop land was affected by the drought during the 2007-2008 crop season. Consequently a reduction of 27.64% in crop yield was observed in comparison with the previous crop season (2006-2007).

The MAJ (2008) reported that wheat and barley are together accounted for 61% of Iran's total annual grain production in 2007-2008 crop season. Both wheat and barley production declined 78% compared with the previous year. Rain-fed wheat production, declined from 16 million tons in 2006–2007 to only five million tons in 2007–2008 and barley production also decreased 50% less than the previous year. Fig. 8 and Fig. 9 represent significant crop production losses (wheat and barley) in comparison with the last year in all provinces.

These results were confirmed by analyses of the agriculture statistic reports derived from MAJ (2008) and USDA (2009).

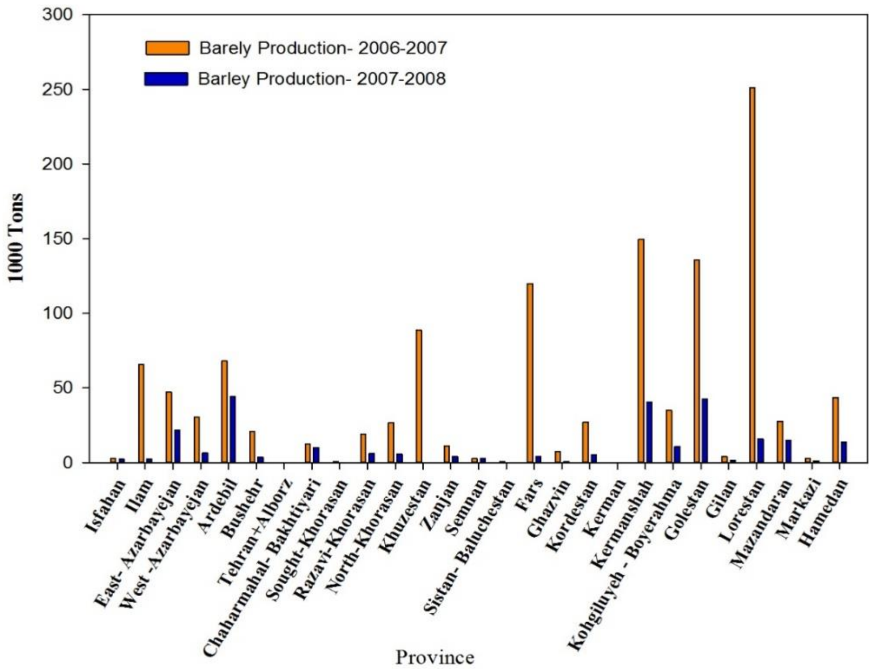

Figure 8. Provincial barley production (rain-fed and irrigated, 1000 tons) in the 2006-2007 and 2007-2008 crop seasons

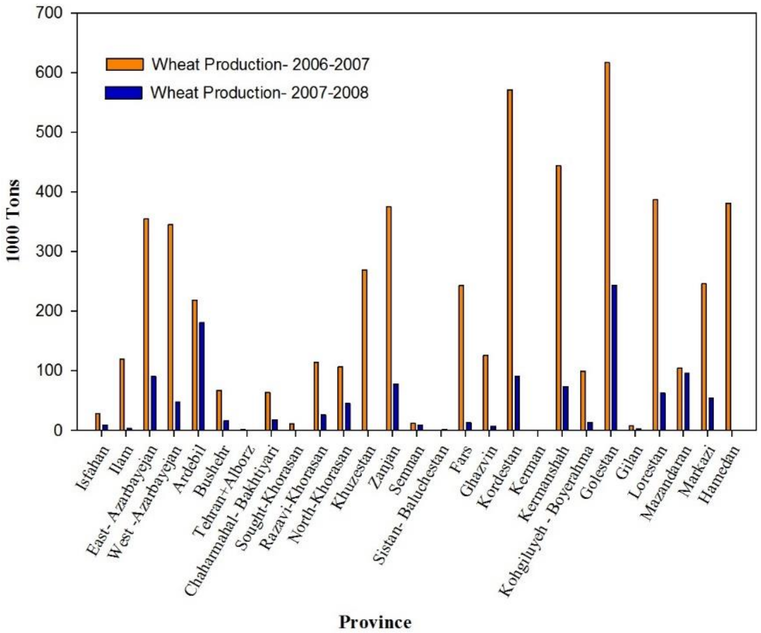

Figure 9. Provincial wheat production (rain-fed and irrigated, 1000 tons) in the 2006-2007 and 2007-2008 crop seasons

According to the United States Department of foreign Agricultural Service (USDA, 2017) reports, with the production in 2008 reduced by the drought, Iran has emerged as one of the world's largest wheat importers, importing approximately 6.8 million tons, compared with importing only 0.2 million tons in 2007-2008.

In spite of the importance of the crop phenology in ASIS, the previous drought studies over Iran using remote sensing (MODIS, AVHRR,) (Keshavarz *et al*., 2014; Safari Shad *et al*., 2017), have not considered the development stages of the crop growth.

Rojas *et al*. (2011) stated that the national and sub national level ASIS results could help analyze the local drought impact on the national crop production. Our study showed that the MODIS-based ASIS maps and information were expected to make a significant contribution to identifying the drought severity and patterns, which in turn would help users and decision-makers in Iran.

Conclusion

This study evaluated the capability of MODIS measurements in modifying ASIS through the analysis of the time series of NDVI, LST, VCI, TCI and VHI images. The original study focused on African croplands and was based on low-resolution AVHRR (16 km) data of the NOAA platforms. The MODIS -based (1 km) drought indices were calculated every 8 days. Furthermore, both phenological timing (SOS, EOS) were also extracted from NDVI data set. By a comparison of the national and sub national crop yields and harvested crops of the area with the ASIS drought maps, the proposed approach demonstrated an advantage in identifying major historical droughts during the observed period and drought conditions monitoring. An investigation of the MODIS-based ASI maps shows that the 2007–2008 crop season had larger areas of severe drought than the others.

In this study, we only used the drought index based on the MODIS indices in Iran Iran's crop lands. Further assessment of the indices in the agricultural drought monitoring using multiple sensors, new weighting scheme and phenological metrics, can be conducted over Iran Iran's crop regions.

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