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Study of Drought Stress Patterns in Khorasan Province using Climatic-Agricultural Indices

Omid Armandpisheh*, Mohammad Bannayan Aval*, Hamidreza Khazaei*, Mostafa Aghaei** and Mohammad Kafi*

**Agronomy Department, Ferdowsi University of Mashhad, IRAN*
***Cereals Department, Seed and Plant Improvement Institute, IRAN*

(Corresponding author: Omid Armandpisheh)
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ABSTRACT: The present study is aimed to evaluate the drought patterns in Khorasan province over the years of 1983 to 2011. Drought conditions using rainfed wheat yield is an indicator reflecting climate conditions and patterns, which is used in agriculture. In the current study, the integration of drought stress indicator suitable with the region conditions (Heat to Precipitation Ratio index), land-spatial analysis for evaluating spatial distribution and drought time patterns during previous years, was used. It identifies some regions (Torbat heydarieh, Ferdows, Gonabad and Ghaen), in which relative harsh drought causes problem for crop production. High amount of HPR was observed in wider part of the province, and higher amounts HPR were seen in cities of Nehbandan and Boshruyeh. In general, time patterns in the present study shows that drought across Khorasan province is accompanied with increasing trend.

Key words: Rainfed wheat, drought stress, climatic agricultural indices, Khorasan province.

INTRODUCTION

The possible effects of plants response to climatic changes are partially analyzed (Easterling *et al.,* 2000; Meir *et al.,* 2006). However, new evidence was reported about the climatic changes effects on agricultural crops (Tao *et al.,* 2006). One of the main concepts in the context of climatic changes is drought, which is the most important hazard in 20th century resulting in billions dollars loss (Bruce, 1994). Drought is one of the main natural risks in all over the world with which large parts of the world face. Due to the increase in frequency and intensity of heat waves in the future, climatic models of drought predict the probability of drought increase in the future (Beniston and Stephenson, 2004). Yet due to clarity in scale and the model output patterns, climatic models may not be compatible with low precipitation regions (Vicente-Serrano *et al.,* 2004). Heat waves and drought have many features in common, and have negative wide effects on crops growth (Mavromatis, 2007). Precipitation shortage in summer and winter can trigger various hydrological effects on soil water storage. The drought history in western parts of Europe has been analyzed by Thomsen (1993) for time period of 1750 to 1989, and the results showed that both kinds of drought (summer and winter) can occur, showing that drought is not just related to warm periods of the year. Drought effects may appear as regional and continental concerns including reduction in precipitation and soil moisture or fluctuation increase in yield and limiting regions suitable for cultivation of traditional crops (Olesen and Bindi, 2002). In the recent decade, yield reduction owing to drought has been dramatically increased, which is originated from vulnerability enhancement in some regions which previously were less vulnerable (Tank and Konnen, 2003). One of the consequences of high temperature and low precipitation is the reduction of soil water storage which is the most important limiting factor for the production of rainfed crops, and can exert various levels of stress on crops (Diodato and Bellocchi, 2007). One example of these conditions was the severe heat waves occurred all over the Europe in 2003 which was accompanied by soil water shortage and severe drought stress. Similar event was occurred in Iran in 2000 which caused serious damage to agronomic crops, particularly in rainfed conditions owing to high heat and severe drought stress.

In order to alleviate the effects of drought stress and brace for its consequences with the minimum economical and social damages, it is necessary to predict the necessary planes. On the other hand, managing the drought requires the existence of comprehensive prediction systems. Drought indicators are good tools for drought prediction systems (Gourabi, 2004). Over the years, several indicators have been developed which can estimate drought intensity (Loomis and Connor, 1992). Each of these indicators needs different input data, therefore each one results in different measurement or different estimation of the drought.

Drought indices originally refer to temperature and specific time duration (for example season or month) related to precipitation shortage in that particular time period in which plant grows. For example, Palmer's drought indicator was one of the indicators used for determination of drought characteristics in major different regions of the world, because it considered both factors of precipitation and evapotranspiration (Diodato and Bellocchi, 2007).

Different methods have been developed for assessment of spatial and temporal patterns in drought conditions, of which is using remote sensing method (Gathara *et al.,* 2002). The other methods are ground surface data (Hisdal *et al.,* 2001; Wilhelmi *et al.,* 2002) or the integration of both mentioned methods (Vogt *et al.,* 2000). Yet none of these methods is completely reliable (Fowler and Kilsby, 2002). Changing remote sensing data into valuable information to detect drought requires accurate understanding of measurement physic and also complex analyzing tools (Vogt *et al.,* 2000). In contrast, climatic data of land surface are easily usable but they have this fault of distance interpretation between stations. In the present research, spatial and temporal patterns across Khorasan province have been studied using rainfed wheat database, the weather conditions recorded in 14 weather stations, and one drought indicator. Drought indicator map and rainfed wheat yield were developed using inverse distance weighting method for Khorasan province. The aim of the present study was to evaluate and analyze spatially drought in the province using drought stress indicators and their effects on rainfed wheat yield.

A. Drought stress patterns in Khorasan

Khorasan province with the area of 248000 km^2 is one of the most important regions for agricultural crops, which is located in northeast of Iran. This wide region with the population of over 6 million plays a crucial role in agricultural and economical sectors. Owing to being large, Khorasan province has different climates ranging from cold northern regions and mild summers to scorching summers and cold winter. The weather conditions in Khorasan are variable, particularly in Mashhad; so it may be possible that weather change reaches 10 to 15°C (Bannayan *et al.,* 2011). Khorasan has a wide diversity in its climatic conditions, yet the majority of farms in this semi-arid region are under reinfed cultivations (Bannayan et al., 2010). Wheat yield in Khorasan province varies from year to year which is largely resulted from the fluctuations in precipitation variability (Bannayan *et al.,* 2011). Average precipitation throughout the province during the last 30 years was about 131 mm, and varied from 222 mm in Nehbandan to 269 mm in the northern regions of Bojnoord, so that precipitation amount in Nehbandan was only 71 mm in 2000 and Bojnoord with 333 mm in 1992 had the highest amount of precipitation. Climate, on the one hand, plays an important role in the province agricultural activities, and on the other hand, it has key role in the environment and the economy of the province to play. Climate role is important as the reason for production variety in local and national scales. Variation in annual yield of agricultural crops, especially for rainfed cultivation, depends primarily on growth and different biomasses of plant that have been obtained under different weather conditions (Gage, 2003).

Furthermore, in recent years, Khorasan climate has changed to drier seasons with lower precipitation. During the time periods between the months of November to May, the precipitation amount in the province is relatively low, and in most years, especially in the mid and late spring season, when the maximum daily temperature exceeds 30 ° C, a long drought stress period can be seen especially for the rainfed crops (Eyshi *et al.,* 2011).

MATERIAL AND METHODS

In this study, drought was studied and analyzed using several indicators of drought stress. One of these indicators is heat to precipitation ratio (HPR) which is derived from data related to temperature and precipitation (Gage and Mukerji, 1977), and then compared with two other relative simple indicators, which both have similar input data. These two indices are the Standardized Precipitation Index (SPI) and Mediterranean crop drought index (MCDI) developed by McKee *et al.,* (1993) and Snyder (2002), respectively. Both of these indices do not require a continuous input data of evapotranspiration, which actually are not also available in meteorological stations of the province. HPR index was developed for the interpretation of the stress caused by drought in the insect population, but later was used for corn. To calculate the index, the following formula is used:

$$\mathrm{HPR} = \frac{\mathrm{MDD_m}}{1 + \mathrm{p_m}} \quad \dots (1)$$

Where, MDDm is cumulative degree days per month and Pm is the precipitation of the same month. When the HPR is high, it suggests that temperature is high and the precipitation is low. Since performance during the growing season is dependent upon the environmental conditions which occur during the plant growing season as well as the conditions that occur in previous months even before plant cultivation, therefore MCDI index was also used which showed, to some extents, the conditions before planting. MCDI calculation formula is as follows:

$$\mathrm{MCDI} = \frac{\mathrm{MDD_m}}{0.55\,\mathrm{p_{m-1}} + \mathrm{p_m} + 30} \quad \dots (2)$$

In both equations 1 and 2, the following equation was used to calculate the cumulative degree days:

$$MDD_m = n\left[\frac{(T_{max}-T_L)^2}{24} + (T_{min} - T_L)\right] \qquad if\ T_l < T_{min} \quad (3)$$

$$MDD_m = n\,\frac{(T_{max}-T_L)^2}{24} \qquad if\ T_L \geq T_{min} \quad (4)$$

Where, T_{max} and T_{min} are the mean of monthly maximum and minimum temperatures, TL is the threshold temperature which is considered 0°C for wheat, and n is the days number per month. Understanding this fact that rainfall has different impacts on water resources, such as groundwater, surface water and snow reserves, led to SPI index to be developed and presented. Indeed, the Standardized Precipitation Index (SPI) was developed to quantify the lack of precipitation at different timely scales ranging from one to 48 months (McKee *et al.,* 1993). The aforementioned scales show the effects of drought on the ability of water resources. One of the most important features of SPI is determining the start and end times of drought, and thus its duration in a region (McKee et al., 1995; Hisdal *et al.,* 2001). Soil moisture conditions response to precipitation fluctuations on a relatively short scale, while groundwater, river flow and storage resources react to precipitation fluctuations in a longer period (Eyshi *et al.,* 2011). SPI in each region is calculated based on the long-term statistics and for the intended period. Positive value of SPI indicates that rainfall is higher than the average rainfall, and negative value means it is reverse. Since SPI is standardized, it can be used for wet and dry climates and the results are comparable for the intended period. According to this method, the drought period occurs when the SPI is continuously negative and reaches -1 or less, and ends when the SPI is positive and cumulative values of SPI shows the magnitude and severity of the drought period (McKee et al., 1993).

Standardized Precipitation Index is calculated by differences in precipitation from the average for a specific time scale, and divided by the standard deviation (McKee *et al.,* 1993):

$$\mathrm{SPI} = \frac{X-\bar{X}}{\delta} \quad (5)$$

Where, X is the amount of precipitation (monthly or annual), $\bar{X}$ is the average precipitation during the studied period, and sigma is the standard deviation of precipitation data. Drought occurs when Standardized Precipitation Index negatively continued, so that it reaches -0.1 or less, and when it is positive, it shows the end of the drought. In the present study, SPI-SL-6 software was used for the calculation of SPI indicator.

Higher correlation (r^2 = 0.21) was observed between wheat yield and HPR index, compared to two other indices (Fig. 1).

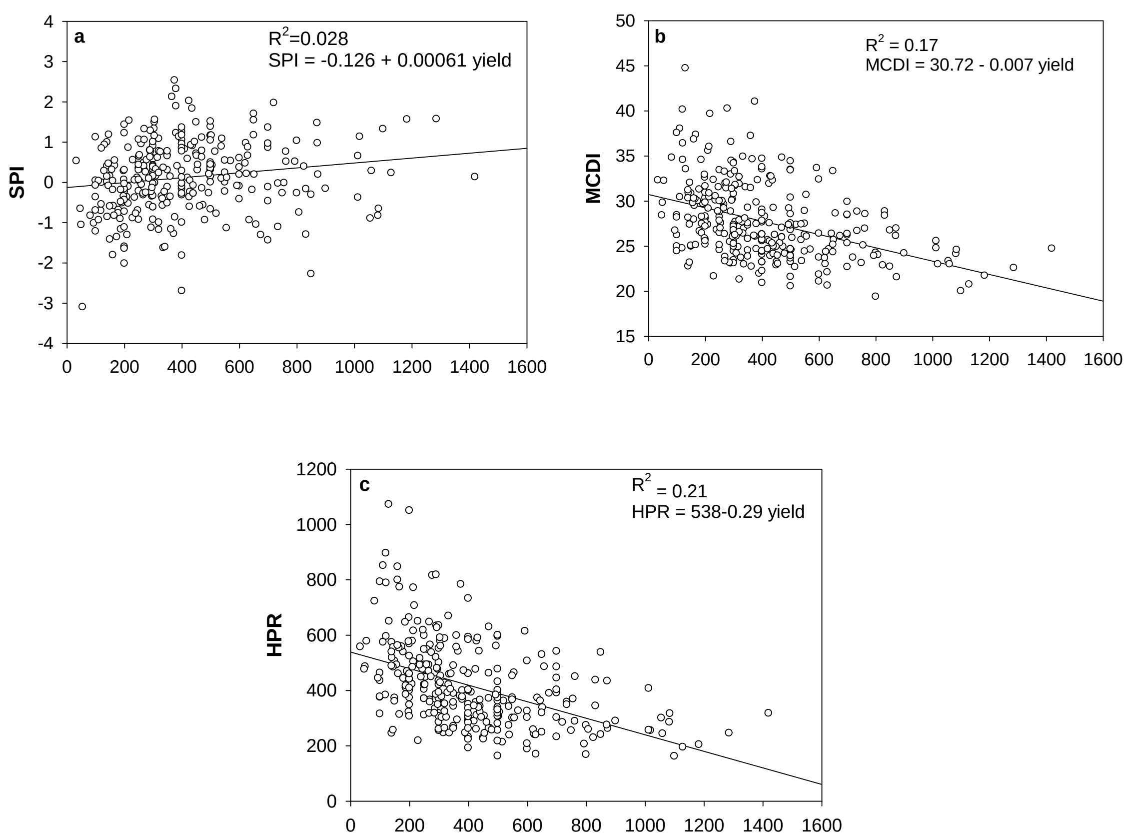

Fig. 1. The relationship between rainfed wheat yield and drought indicators (a) Standardized Precipitation Index (SPI), (b) Mediterranean Crop Drought Index (MCDI) and (c) heat to precipitation ratio (HPR) indicator for the period between years of 1983 to 2011 in Khorasan province. The three indices all were calculated between months of November to May.

A. Drought spatial analysis

For interpolation and estimation of HPR status in some parts of Khorasan, where there is no data of the places, inverse distance weighting method (IDW) was used. Inverse distance weighting method is one of the methods used widely in geographical studies (Faraji and Azizi, 2005). The basic concept of this method is that by increasing the distance, the amount of parameters impact in estimation of unit level decreases. To predict the locations where their data are not measured, measured data around the place were used. In anticipation, the weight factor is determined based on the distance of points from each other. To places close to and far from the sample place, more and less weight was given, respectively. The following equation can be used to obtain the values of different points.

$$z = \frac{\sum_{i=1}^{N} \frac{z_i}{d_i^m}}{\sum_{i=1}^{N} \frac{1}{d_i^m}} \pi r^2 \qquad (6)$$

Where, z_i is the sample values, di is Euclidean distance of each location to the sample place, m is the power factor (distance friction) and n is the number of sample points. The amount of weight loss is dependent on the amount of m. If m is considered equal to zero, the weight loss, therefore, is not created with the space. Thus weight at the space level is assumed to be equal. By increasing the amount of m, weight for farther points, decreases more quickly; if m amount is too large, observable points will only affect the forecast. Another factor affecting the inverse distance weighting (IDW) is the number and the location of the adjacent points or, in other words, the situation of neighboring units. So choosing and limiting the number of adjacent points and, in other words, search window for nearby locations is important in analysis (Faraji and Azizi, 2005). All calculations of inverse distance weighting method for spatial analysis were performed in ArcGis-ESRI software (Johnston *et al.*, 2001).

RESULTS AND DISCUSSION

The relationship between rainfed wheat yield and cumulative HPR index (between the months of November to May) over time (1983-2011) in Khorasan province are shown in Fig. 2. With increasing drought HPR index, anomaly amount was reduced, which in fact HPR increase represents an increase in the possibility of drought.

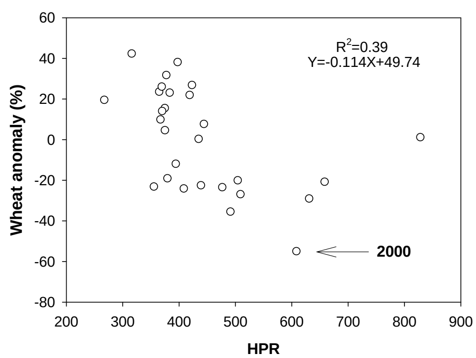

Fig. 2. The relationship between rainfed wheat yield anomaly with cumulative HPR index during the months of November to May over time period (1983-2011) in Khorasan province.

The annual fluctuations in Khorasan wheat yield are mainly related to climatic factors, and drought stress fluctuation greatly shows its effects on yield fluctuation. It is notable that severe drought that occurred in Iran in 1999-2000 led to an increase in HPR and yield anomaly drop in Khorasan, so that the lowest amount of anomaly over 28 years of the study (- 55.2) was due to the year of 1999-2000.

A. Timely trends of drought during growing season of rainfed wheat

Timely analysis of drought was performed during 1983 to 2011. To test the timely trend, HPR amount between the months of November to May was used. These months were chosen because they were coincided with the growing seasons of rainfed wheat, and the aim was to study the effect of these months on the productivity of rainfed wheat. Annual fluctuations of HPR for the related months are shown in Fig. 3.

HPR levels in recent years in most months of wheat growing season (except for December and January) showed an increasing trend, indicating the climatic changes that have happened in Khorasan province over the three previous decades and resulted in more severe drought. Our results are in accordance with the results reported by some others researchers for Khorasan province (Faraji and Azizi, 2005).

Anomaly annual percentage of cumulative HPR from November to May between the years of 1983 to 2011, seen in Fig. 4, shows a certain pattern of positive values in recent years, which in turn reflects the increasing droughts in recent years. This pattern was a notable pattern for Khorasan which reached + 54% in year of 2000. Study of HPR obtained for regions with different latitudes (North, Centre and South of Khorasan) showed the significance of seasonal patterns (Fig. 5).

In Fig. 5, HPR average for 1983 to 2011 time period is shown, and 2000 HPR values for each classification of North, Razavi and South Khorasans are more clearly specified. In July 2000, HPR value in North and Razavi Khorasan was, to some extent, lower than the critical point. Yet the highest amount of HPR value in 2000 in the three North, Razavi and South Khorasans occurred in August. Studying each of the three regional classifications showed that severe drought phenomenon in 2000 almost affected the entire province (Khorasan).

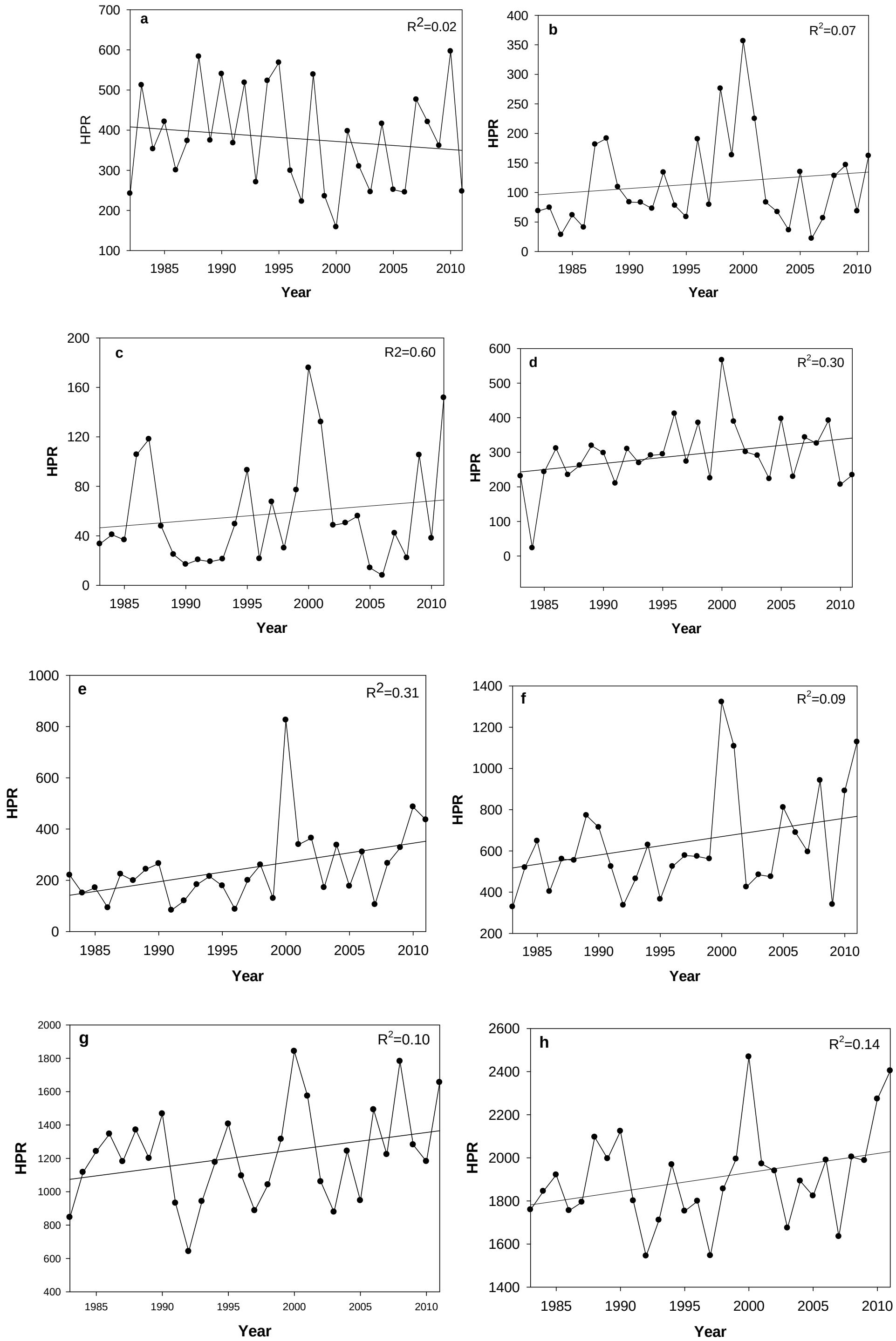

Fig. 3. HPR values fluctuations in Khorasan province between the years of 1983 to 2011 for months of November (a) to May (h).

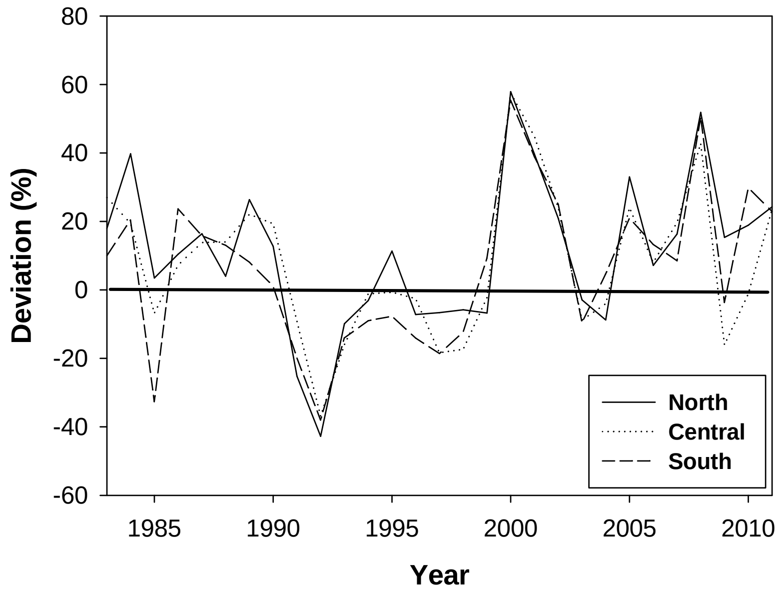

Fig. 4. The percentage of deviation from HPR means (1983 to 2011) between the months of November to May.

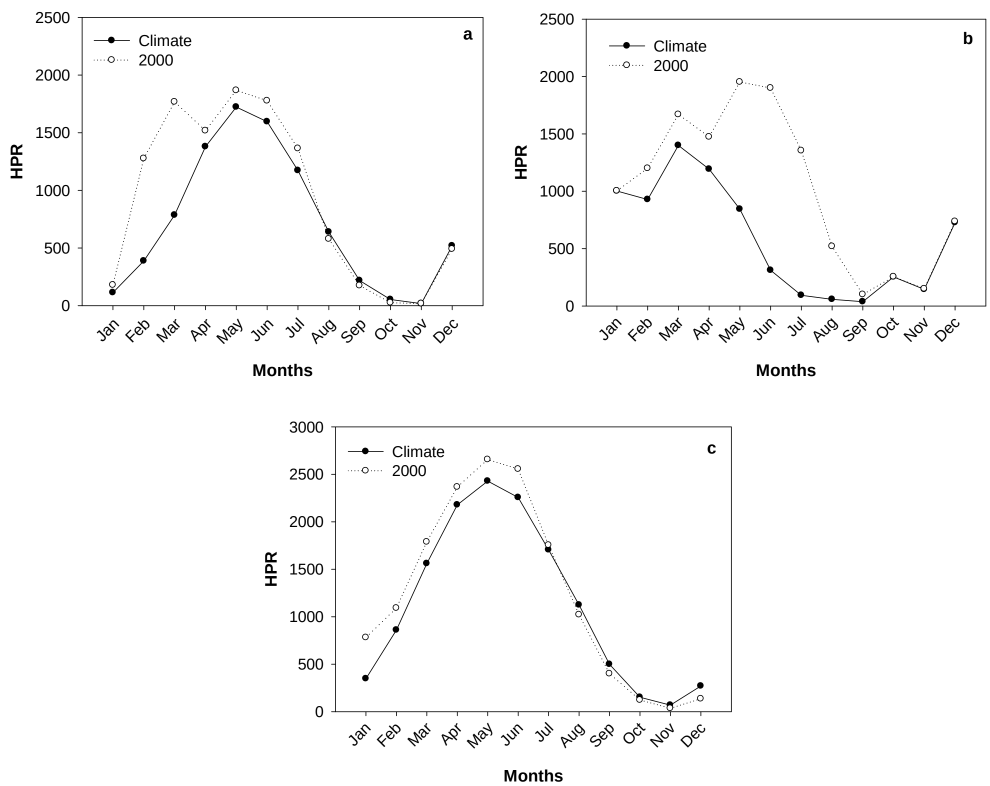

Fig. 5. Monthly values of HPR index for the year of 2000 and long-term average of HPR index between the years of 1983 to 2011 (a: North Khorasan, b: Razavi Khorasan and c: South Khorasan).

B. HPR spatial pattern and rainfed wheat yield in Khorasan province

To determine the spatial distribution of drought stress over the time throughout the province, HPR surface maps were produced.

Based on the HPR values in each region, two maps were drawn for the cumulative HPR values of November to May. Fig. 6a shows the time period, and Fig. 6b shows HPR values for 2000, when the drought was more severe than other years.

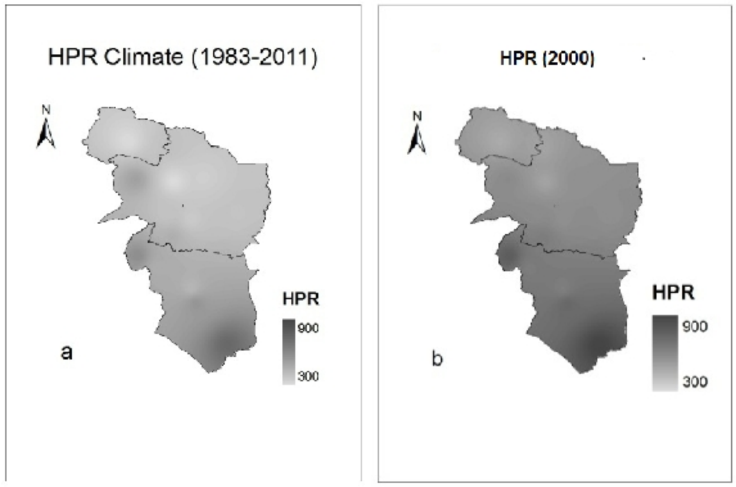

Fig. 6. (a) The spatial pattern of HPR index between the months of November to May for a long period of 29 years and (b) relatively severe drought in the year of 2000.

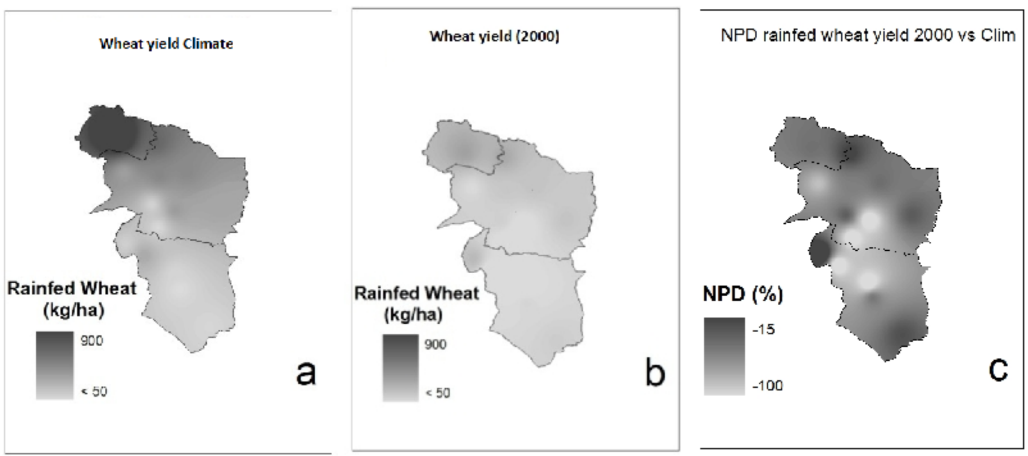

Fig. 7. (a) The spatial pattern of long-term average of rainfed wheat yield (b) yield in year of 2000 and (c) the percentage of normalized difference of the average long-term yield compared to 2000.

According to the climatic period, high HPR values were observed in warmer climate. However, high levels of HPR were seen in wider part of the province in 2000, and the higher HPR values were due to cities of Nehbandan and Boshruyeh.

Under the normal conditions of drought, agriculture sector is often the first part that is affected by drought due to the dependence on soil water storage, since soil water is depleted rapidly in drought period and rainfed wheat dependence to soil water content is high, an issue that almost occurred in the entire province in 1999-2000. The difference between 30 years (1983 to 2011) of rainfed wheat yield is shown in Fig. 7. To estimate the difference the yield over the 30 years from the year of 1999-2000, the following equation was used:

$$NPD = \frac{Y_{2000} - Y_{baseline}}{Y_{baseline}} 100$$

The difference between 30-year period and 2000 is almost clear throughout the province, but this difference was less evident in northern regions of Khorasan province, because better rainfall in North Khorasan created more balanced drought conditions in the area.

CONCLUSION

Drought is one of the most important natural disasters around the world, which annually causes, on average, between 6 and 8 billion dollars damage to different countries. Given the consequences of drought, it is important to assess the severity of the drought, but the exact amount of the drought is difficult to determine.

Majority of simulation studies are about the future climate changes and its effect on the performance of agricultural crops; and relatively little research has been conducted on the effects of climate changes that have already occurred and brought about different effects on agricultural production.

Quantitative analysis of climate changes on living organisms and the environment represents an important challenging research. Agricultural systems are very sensitive to climate changes, and plant performances in previous years can be an important indicator that shows the close relationship between climate changes and the environment. The present study is an evaluation of three indicators of drought stress, among which HPR and SPI indices are almost old indices and MCDI index is relatively new. In this study, HPR index was used for quantitative evaluation of drought conditions distribution in relation to rainfed wheat yield in Khorasan province. HPR index showed the effect of climate changes that has occurred in the province during the last 30 years. The drought has caused, so far, a lot of damage to crops in the province. Estimating the costs caused by the drought is not considered in this study. However, it is clear that continuation of climate changes trend will bring about an increase in the amount of damage caused by drought in the province. Furthermore, rainfed wheat farming in some areas of the province that has been under rainfed cultivation will be remained uncultivated, leading agricultural sector to face a huge economical loss. Oscar *et al.,* (2004) proposed a scenario in which air temperature along with greater dryness during the summer season have increased significantly in recent decades, leading to a reduction in soil water storage. This might be a good explanation for the unusual drought occurred throughout the Europe in 2003 or relatively severe drought that affected Iran in 1999-2000. In addition, increase in drought periods primarily associated with a higher incidence of intense rainfall, which can be a potentially dangerous combination for soil erosion (Sauerborn *et al.*, 1999).

Identifying the boundaries of the weather (regions with homogeneous climate) of drought scenarios at regional and sub-regional scale, which is investigated in this study, is significant to understand the characteristics of the climate and their potential impact on the agro-ecosystem. The results obtained from this study are an encouragement and justification for using GIS and geospatial technology along with interpolation to obtain drought index maps, as spatial and temporal variability and multiple drought effects require an improvement in existing tools and data for mapping and monitoring the drought phenomenon.

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