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Assessment of climatic indices limiting rainfed wheat yield

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ABSTRACT

In this study variation of six climatic indices including accumulated precipitation (*P*), accumulated potential evapotranspiration (PET), accumulated actual evapotranspiration (AET), accumulated crop evapotranspiration (ETC), accumulated water stress (*S*) and climatic water deficit (*D*), was investigated. Climatic indices and their variation were calculated during seven growth stages of wheat in five locations in the northeast of Iran from 1983 to 2008. Principal component analysis (PCA) technique was applied to explore major modes of variation in the regional climatic indices during different crop growth stages. The principle component obtained for each region was correlated to the regional winter wheat yield. Finally the regional amount of water and precipitation use efficiency (WUE and PUE) were analyzed in order to assess any possible association with wheat yield. The results showed that the highest precipitation occurred during the tillering stage and spatially decreased from north (Bojnord) to south (Birjand) and from east (Mashhad) to west (Sabzevar). The difference between the highest and the lowest precipitation across all locations was 2.5 of standard value. The variation pattern of AET, compared to other indices, showed more similarity to variation of precipitation at different growth stages and the highest AET (more than 2 of standard value in all locations) occurred during the tillering stage. The PCA indicated that effective components varied in different locations. The most positive and effective components were types of evapotranspiration that are associated with crop (ETC and AET) and precipitation. However none of these effective PCs showed a significant correlation with final yield. The PUE and WUE analysis indicated that PUE provides more information to interpret the relationship between total amounts of precipitation and the final yield.

1. Introduction

Iran characters a diverse climate conditions from arid to humid with annual average precipitation of 250 mm (Bannayan et al., 2010; Ashraf et al., 2014). Availability of water rather than land is the main constraint for agricultural production in arid and semi-arid environments (Bannayan et al., 2008). Such condition when combined with heat stress will be of major limitation to food production worldwide, especially in areas that rainfed agriculture plays the main role in food production (Hossain et al., 2012). Wheat (*Triticum aestivum* L.) is the most important cereal in the world and according to the International Food Policy Research Institute (IFPRI) projections, the world demand for wheat will rise from 552 megaton in 1993 to 775 megaton by 2020 and 60% higher by 2050 (Hossain and Teixeira da Silva, 2012). Many studies have shown that increment of temperature will likely reduce the wheat production by 20–30% especially in developing countries (Lobell et al., 2008; Rosegrant and Agcaoili, 2010). This crop is the primary staple food of the people of many countries. Rainfed wheat accounts for about 60–65% of the farm land cultivation in Iran and contributes 30–35% of national wheat production. It is also expected that the national demand for wheat will increase by over 20 megaton by 2025 (Nassiri et al., 2006). The northeast of the country (Khorasan provinces) is one of the main regions of wheat cultivation (Eyshi Rezaei and Bannayan, 2012). Agriculture in this region is mainly rainfed though annual variability of both precipitation and seasonal onset of the rain in addition to almost no precipitation during the summer have been reported too (Bannayan et al., 2010; Khazaie et al., 2008). Realizing the reducing crop yield factors is important for yield estimation at regional scales and also to improve crop management methods. Moreover determination of these factors is essential for the development of adaptation strategies to climate change impact (Qian et al., 2009).

The IPCC has reported that climate change over the next century may affect precipitation pattern in many parts of the arid

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regions and total precipitation may decrease by about 20% or more (IPCC, 2008). This is so crucial for anywhere that rainfed crop production is very vulnerable to dry conditions. Even if precipitation amount and pattern do not change, higher risk of drought occurrence will adversely affect wheat yield (Bolle, 2003). Drought due to low precipitation or high temperature, is one of the main factors that limits the success of modern agriculture around the world. Drought is also one of the most effective environmental conditions which detrimentally impacts the growth, development and production of many crops (Hasanuzzaman et al., 2012). Drought impact intensity depends on the crop development stage at the time of drought occurrence (Lopez et al., 2003). Crops that are exposed to drought stress accelerate their development and complete all the developmental stages within a shortened period of time which finally result in lower yield (Hakim et al., 2012). Rosenzweig and Parry (1994) projected that cereal production in developing countries will decrease by 2060, so prices and thus the population at risk of hunger will increase despite adaptation. Nassiri et al. (2006) predicted that the semiarid areas of Iran are so sensitive to drought and vulnerable to climate changes in next decades.

It is important to understand the most effective factors on the growth and yield of wheat to prepare responsive strategies to future climate change. Principal component analysis (PCA) is a technique to transform a given set of characteristics (variables), which are mutually correlated, into a new system of characters known as principal components (PCs) which are not correlated (Rymuza et al., 2012). This technique has been used in some studies for analysis and assessment of effective factors on crop yield production. PCA is suitable for multivariate analysis of intercorrelated data such as agroclimatic factors limiting crop yields (Qian et al., 2009). To explore a new analysis method, Wigley and Qipu (1983) decomposed both yield and climate data time series into principal components which were then related using standard multiple regression. Salchow and Lal (2001) applied the PCA to associate corn and soybean yield to the measured physiographic attributes of a landscape with soil erosion. Reynolds et al. (2007) investigated the association of source/sink traits with wheat yield in a high-yield environment by using PCA, based on the correlation matrix using the PRINCOMP procedure of SAS. Qian et al. (2009) employed PCA to explore major modes of joint variability in the regional water-related agroclimatic indices at five growing stages of spring wheat. Cai et al. (2011) developed a Principal Component Regression (PCR) model to estimate the historical relationships between weather and crop yields of corn, soybeans, cotton, and peanuts for several northern and southern U.S. States. In their study, weather factors, instead of using directly, were transformed from original weather variables by the PCA. Rymuza et al. (2012) used PCA for the complex assessment of spring wheat characteristics and reported that it is a useful technique for reduction of original characteristics to a new variable that contains most information of the input data. Bornn and Zidek (2012) used the wavelet and PCA methods for modeling of crop yield in the Canadian Prairies as a function of climate-related explanatory variables such as water stress index and growing degree day for 40 agricultural regions from 1976 to 2006. Their results showed that, PCA provides better model fit and better prediction than the wavelet method.

Agriculture in the northeast of Iran heavily depends on rainfed cereals production and the region has usually been affected by drought occurrence (Bannayan et al., 2010). Any possibility to enable farmers to achieve higher crop productivity and mitigate the negative impacts of climate change in this region is highly required. The aim of this study is to achieve a better realization of the climate effects through climatic indices at different crop growth stages on regional rainfed wheat yields in order to increase or prevent to decrease the wheat crop production in this area.

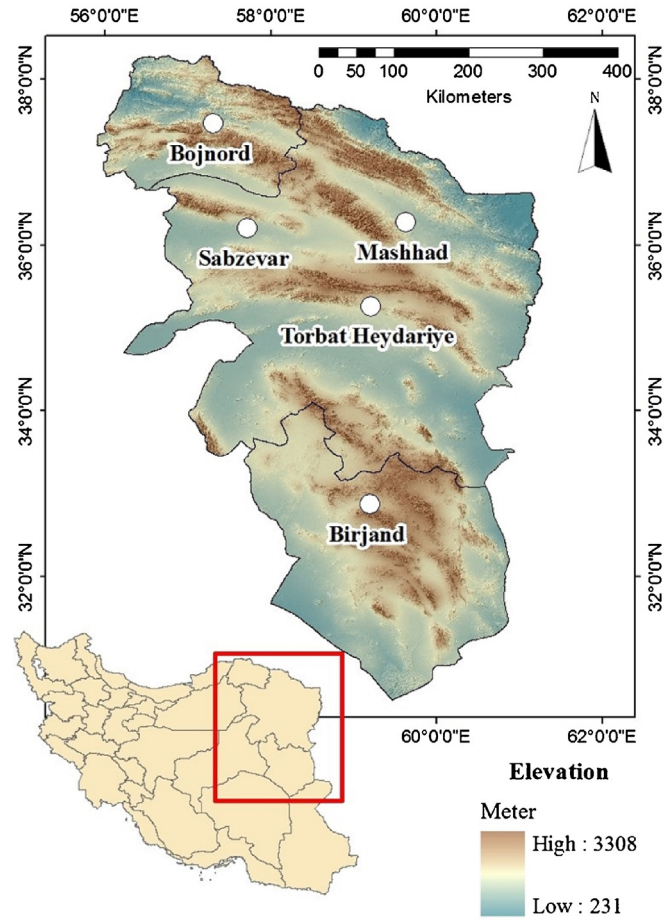

Fig. 1. Geographical distribution of five study locations in northeast of Iran.

2. Materials and methods

2.1. Study area, weather and yield data

In this study five regions in the northeast of Iran (Khorasan) were considered (Fig. 1) due to availability of historical weather and winter wheat grain yield data. Table 1 shows the physio-characteristics of the study regions. Daily weather data from 1983 to 2008 of all study regions were obtained from local synoptic stations. These include minimum and maximum temperatures (°C), sunshine hours (h), relative humidity (%), wind speed (m s^{-1}), and precipitation (mm). Spatial distribution of precipitation and temperature during above time period for study regions has been presented in Fig. 2A and B, respectively. Generally there is a reducing pattern of precipitation amount from north (more than 240 mm) to south (less than 160 mm) and east to west as approaching to Central Iranian Desert. There is a reverse spatial trend in temperature (more than 2 °C) but reduction of precipitation from north to west is significantly higher than increasing trend of temperature. The climate of Khorasan (Fig. 2C), according De Martonne index, is arid and semiarid. The agricultural activities in this region are mainly rainfed, however, the precipitation variability is high (Bannayan et al., 2011).

Wheat is the major crop in northeast of Iran with "cultivation area" of 210,734 ha and the local farmer's economy depends on the production of this crop. The planting date of wheat is not on a specific date and mainly depends on the precipitation in autumn. The harvesting date also depends on summer temperature around the end of spring or early in summer. Therefore wheat production

Table 1
Latitude, longitude, elevation and annual average of weather variables for five study locations in northeast of Iran.

Location	Longitude (E)	Latitude (N)	Elevation (m)	Average minimum temperature (°C)	Average maximum temperature (°C)	Total precipitation (mm)
Birjand	59° 12′	32° 52′	1491.10	8.40	24.56	158.42
Bojnord	57° 19′	37° 28′	1091.12	8.43	21.52	253.37
Mashhad	59° 38′	36° 16′	999.20	7.03	21.18	245.29
Sabzevar	57° 43′	36° 12′	977.61	10.62	24.18	187.55
Torbat heydarieh	59° 13′	35° 16′	1450.82	8.59	21.77	252.10

under rainfed totally depends on local climate (Bannayan et al., 2010). The rainfed wheat yield data were obtained from the Statistics and Informatics Center of agriculture ministry. The wheat yield represents the average grain production per hectare for the harvested acreage. The spatial distribution of wheat yield in study period shown in Fig. 2D. This figure shows that there was a wide range of variation in yield from Bojnord in north (~850 kg/ha) to Birjand in south (~200 kg/ha). The spatial distribution of wheat yield was more similar to precipitation distribution (Fig. 2A) than temperature distribution pattern (Fig. 2B) and higher precipitation (in semi-arid areas compared with arid areas) years were along with higher crop yields.

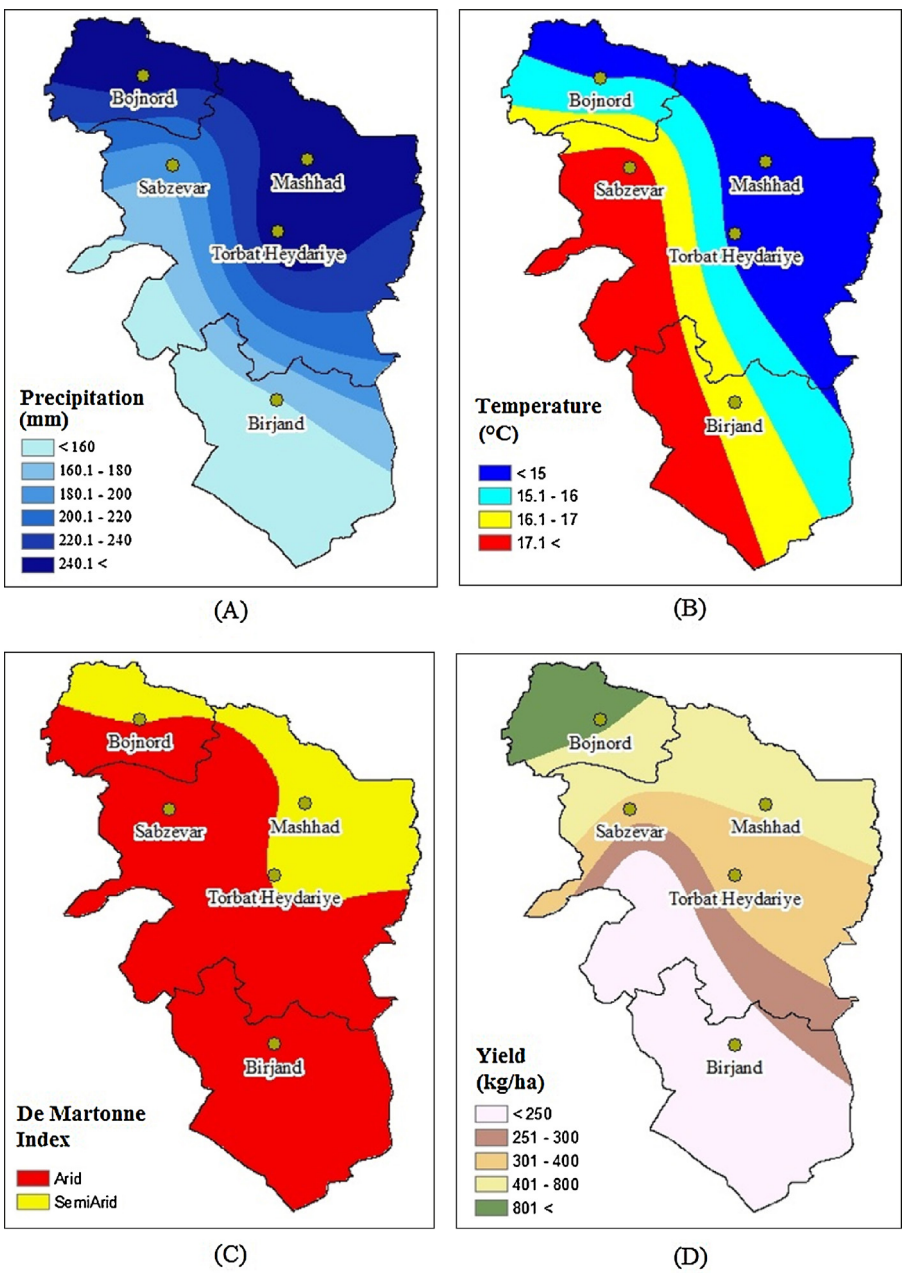

Fig. 2. Spatial distribution of precipitation (A), temperature (B), climate type (C) and rainfed wheat yield (D) of five study locations in northeast of Iran during 1983–2008.

2.2. Climatic indices

Six climatic indices for seven growth stages of wheat including emergence, three leaf stage, tillering, shooting, heading, flowering and maturity were calculated in this research. The climatic indices included accumulated precipitation (P), accumulated potential evapotranspiration (PET), accumulated actual evapotranspiration (AET), accumulated crop evapotranspiration (ETC), accumulated water stress (S) defined as 1 − (AET/PET) and climatic water deficit (D) defined as PET–AET.

Potential evapotranspiration was calculated using the FAO Penman–Monteith method (Jensen et al., 1990) and then was used for calculating crop evapotranspiration based on FAO (1998):

$$\mathrm{ETC} = \mathrm{PET} \times \mathrm{Kc} \tag{1}$$

The wheat crop coefficients (Kc) were used according to FAO guidelines (FAO, 1977). The actual evapotranspiration (AET) calculated as (Sultan et al., 2010):

$$\begin{aligned}\mathrm{AET} &= 0.732 - 0.05\mathrm{ETC} + (4.97\mathrm{ETC} - 0.661\mathrm{ETC}^2) \\ &\quad \times \mathrm{MR} - (8.57\mathrm{ETC} - 1.56\mathrm{ETC}^2) \times \mathrm{MR}^2 \\ &\quad + (4.35\mathrm{ETC} - 0.88\mathrm{ETC}^2) \times \mathrm{MR}^3\end{aligned} \tag{2}$$

where MR is moisture ratio, ranging from 0 to 1 and calculated as:

$$\mathrm{MR} = \frac{P}{\mathrm{AWC}} \tag{3}$$

where P is the precipitation of a given time step and AWC is the available water capacity or the available water content and defines the range of available water that can be stored in soil and would be available for growing crops (Richards and Wadleigh, 1952). Available water capacity is the fraction of total available water (TAW) that a crop can extract from the root zone without suffering water stress (FAO, 1998):

$$\mathrm{AWC} = P \times \mathrm{TAW} \tag{4}$$

where P is the average fraction of TAW that can be depleted from the root zone before moisture stress. Total available water is the water held in soil between its field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}) or the amount of water that a crop can extract from its root zone, and its magnitude depends on the type of soil and the rooting depth (Z_{r}):

$$\mathrm{TAW} = 1000(\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}) \times Z_{\mathrm{r}} \tag{5}$$

Therefore, six agroclimatic indices for seven time periods in five different locations constituted of 210 variables were employed in the analysis.

2.3. Principle component analysis (PCA)

Principle component analysis is a variable compression technique. Using PCA technique, a large number of interrelated variables can be converted to a smaller set of uncorrelated principal component (PCs) which are linear combinations of the original variables (Qian et al., 2009). Therefore, each principal component contains information of all climatic variables. It creates the same number of climate factors as the primary variables and orders them by the magnitude of variances (Cai et al., 2013). The first PC accounts for as much of the variability of the data as possible, and each following PC accounts for as much of the remaining variability. PCA is mainly used as a technique in exploratory data analysis and for making predictive models. The PCs are suitable predictors in multiple regression models, because they are uncorrelated (Qian et al., 2009). In this study six climatic indices were considered for seven time periods constituted of 42 climatic variables in the multivariate analysis. Then the principle component of each region were correlated to the regional winter wheat yields.

2.4. Water and precipitation use efficiency (WUE, PUE)

Water use efficiency (WUE) is defined as the yield (e.g. wheat grain) per unit of crop water use (amount of water lost by evapotranspiration). It is an important agronomic measure for plant production especially in dryland cropping systems (Neilsen et al., 2005). WUE is highly important in rainfed system where a limited amount of water from the rainy season has to last for the whole plant growth period. Precipitation use efficiency (PUE), an alternative to water use efficiency, is equally effective for assessment of water use in long-term rainfed systems (Varvel, 1995). In this study the regional amounts of these factors along with any possible association with climatic indices were analyzed. The average of WUE and PUE from 1983 to 2008 were calculated as below (Campbell et al., 2007):

$$\mathrm{WUE} = \frac{Y}{\mathrm{PET}} \tag{6}$$

$$\mathrm{PUE} = \frac{Y}{P} \tag{7}$$

where Y is yield of wheat (kg/ha).

3. Results and discussion

3.1. Modes of variation of climatic indices

Standardized variation of six indices at seven growing stages for study regions during 1983–2008 are shown in Fig. 3. The highest precipitation occurred during the tillering stage from north (Bojnord) to south (Birjand) and from east (Mashhad) to west (Sabzevar). Temporal distribution of precipitation during crop phenological stages was also different in different locations. In Bojnord the highest and lowest precipitation during crop phenology showed a high variability with about 1.1 of standard value. This variability was more than 2 of standard value for Birjand. The total difference between the highest and the lowest precipitation during crop phenology stages in all locations was about 2.5 of standard value. The temporal distribution of precipitation did not show a significant coordination to the temporal pattern of crop evapotranspiration (ETC) or water demand of wheat crop. The highest precipitation occurred during the tillering stage which is not the most sensitive crop growth stage of wheat to water stress. In Bojnord that has the highest yield among the study regions, significant precipitation occurred during the maturity stage while this stage is the final stage of growth and therefore precipitation at this time is not required and even can impose negative effects on final yield. Actual Evapotranspiration (AET) which is theoretically affected from precipitation in each growth season also has more variation and their variation pattern resembles to variation of precipitation but AET is more variable than precipitation during the whole crop season. The highest AET (more than 2 of standard value in all stations) occurred during the tillering stage in accordance with the precipitation as expected. Minimum values of standard AET never reached to −1.0 of standard value. In the regions which had more precipitation during flowering (like Bojnord in north) higher increase of yield can be expected because this stage is the most sensitive crop development stage. The minimum AET was observed during the heading stage and about −0.8 of standard value. S and D factors did not show any relationship with the final yield. Inefficiency of these two factors in yield interpretation maybe related to the methods of their calculation. They both

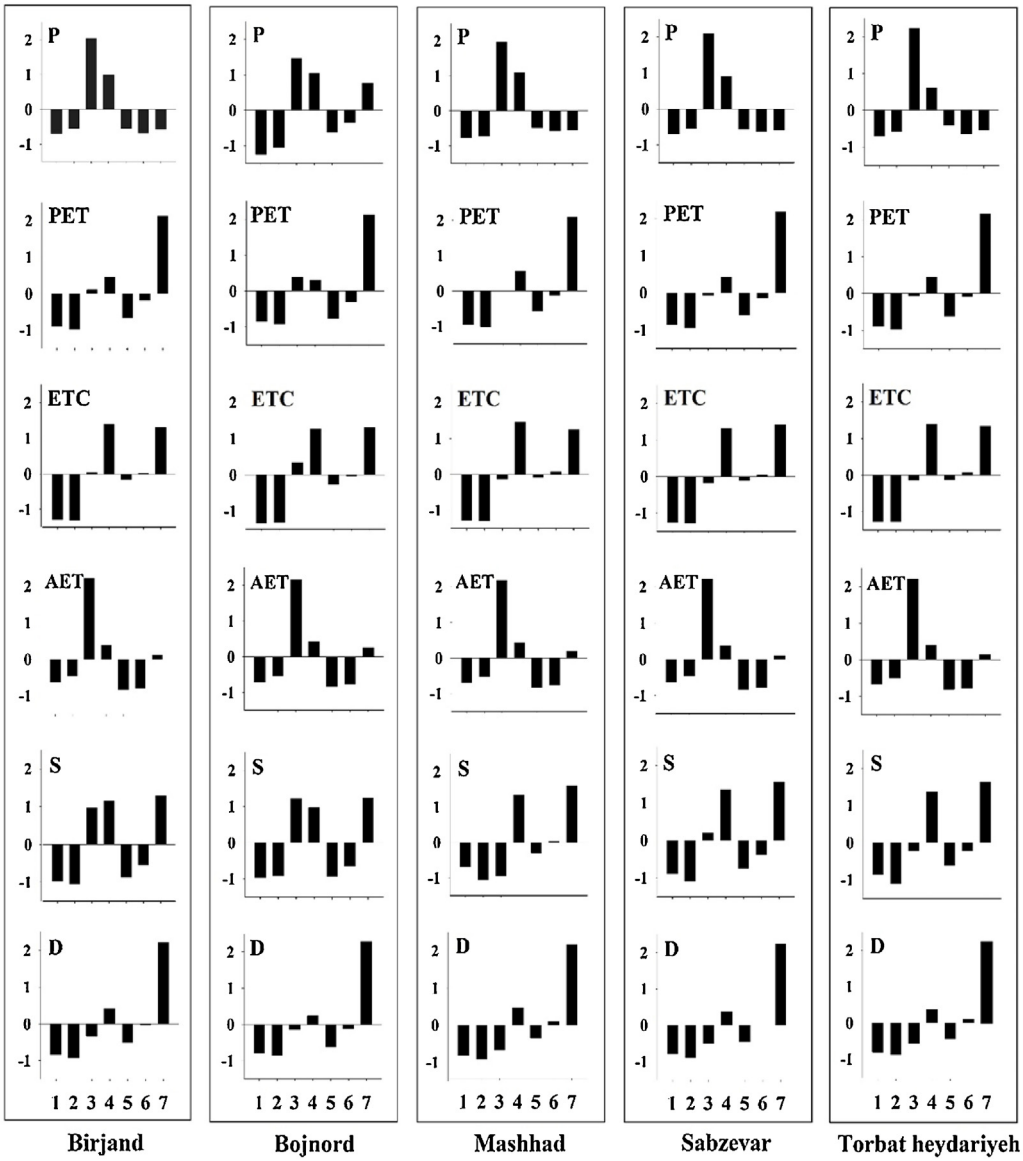

Fig. 3. The standardized variation patterns of six indices at seven growing stages of rainfed wheat for five study locations in northeast of Iran during 1983–2008.

show the deficit amount of water regarding reference evapotranspiration (PET) while it cannot give enough information about the water demand of wheat. There was a similarity between *S* and *D* at maturity stage as both showed the highest value (about 1.5 and 2 standard values for *S* and *D*). In the other crop phenology stages although similarities can be found but the differences in their values are stronger than the similarities in these two indices.

3.2. Principle component analysis of climatic indices

PCA was performed on the six indices for seven crop growth stages during the years 1983–2008. In order to reduce the number of predictor variables, only the first and second PCs as the main predictor variables will usually be considered (Martinez et al., 2009), therefore in this study all of 42 calculated indices were classified into 8 main groups. The percentage of variance was explained by these first eight PCs and the correlations between them and regional rainfed wheat yield are presented in Tables 2 and 3 respectively. These groups justified almost more than 90% of variation of the data (per row in Table 2) but the effective components varied in different locations and were not exactly the same (Table 3) that seems, its may be associated with regional climatic characteristics. Investigation of the name of PCs that have been presented in Table 3 showed that, the most positive and effective classes could be the types of evapotranspiration that are associated with crop (ETC and AET) and showed the sensitivity of plant to these factors especially in final stages of growth. In addition, cumulative precipitation and AET during the primary stages showed the least role among the classes. In some locations like Torbat heydarieh and Mashhad precipitation showed stronger effect in comparison to evapotranspiration. Table 3 shows that, except for 2 cases, none of the components showed a significant correlation with the final yield. The first case was PC1 (ETC7) for Birjand that showed a close correlation of −0.56 with yield at 0.01 percent of significance. The second case was PC6 (P6) for Mashhad and although these factor indicated a good significant correlation with yield (0.60), but could not be a good predictor variable for yield estimation because of the low rank of this component and its poor variance (6.31 in Table 2) in total components (6.31 in Table 2). In general it is clear that the style of variation of climatic indices were identified by PCA have some implication for the effect of variability of an individual regional factor at final yields in each area.

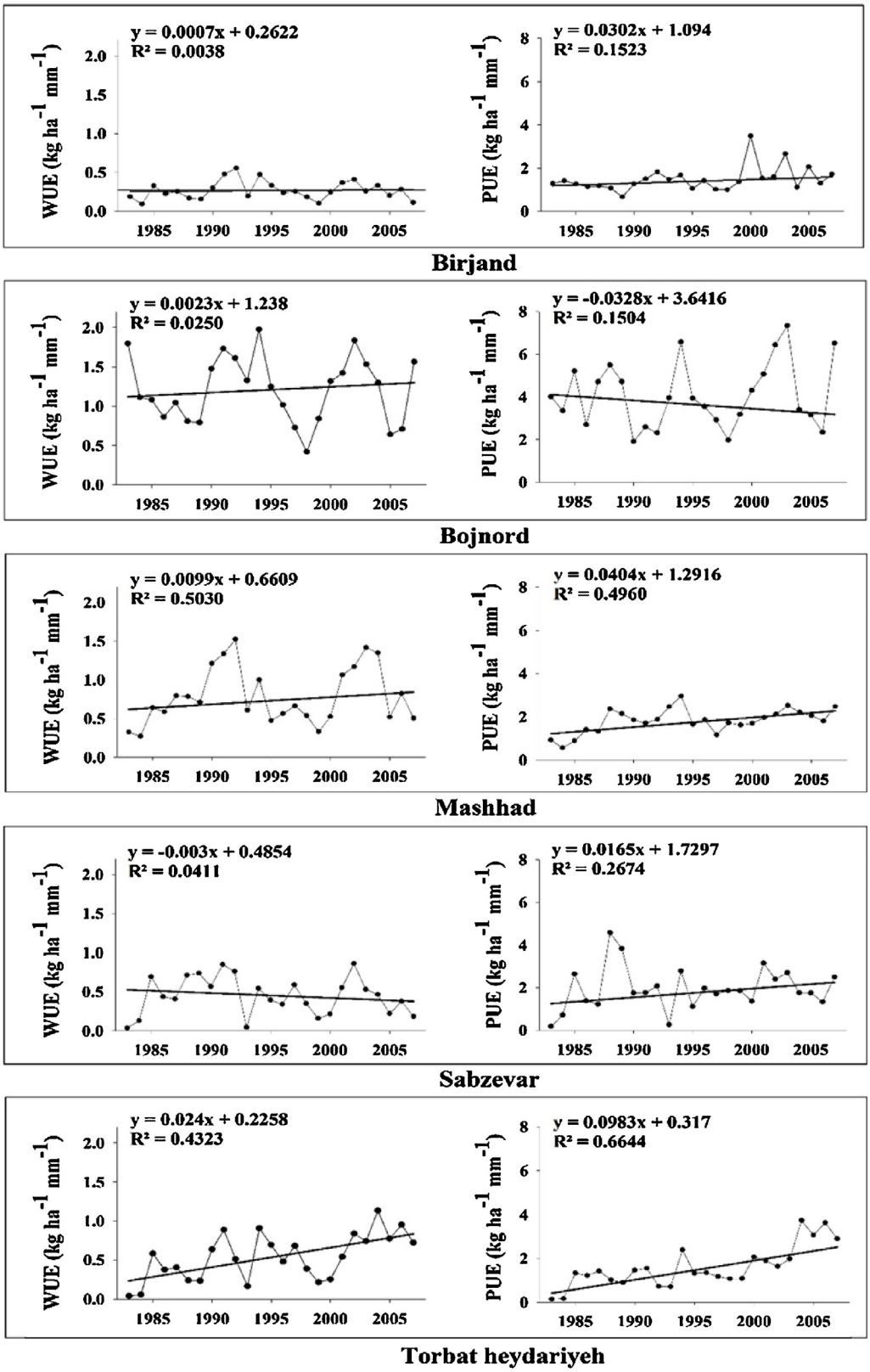

Fig. 4. Water and precipitation use efficiency for five study locations in northeast of Iran during 1983–2008.

3.3. Modes of variation of WUE and PUE

Analysis of WUE and PUE (Fig. 4) requires attention to the extreme values which are significantly high or low. It is due to this fact that high PUE may come along with large amounts of precipitation or low PUE associates with small amounts of precipitation. While high values of PUE should show, high yield in low precipitation and low values of PUE should show the coincidence of low yield and high precipitation. Among the study locations, Bojnord (with highest yield) showed the highest PUE. In this

Table 2
Percentage (%) of explained variance by the principal components (PCs) for five study locations in northeast of Iran during 1983–2008.

Location	Order of PC							
	1	2	3	4	5	6	7	8
Birjand	25.88	18.56	11.82	9.41	8.52	7.28	5.69	3.55
Bojnord	26.63	21.11	9.99	9.44	7.77	5.25	4.65	3.54
Mashhad	33.59	15.66	10.17	8.66	7.33	6.31	4.63	3.59
Sabzevar	26.94	15.94	14.39	9.71	7.98	6.53	5.23	3.03
Torbat heydarieh	29.73	20.68	10.69	8.33	7.38	5.89	4.29	3.48

Table 3
The correlation coefficient (r) between the first eight PCs and rainfed wheat yields for five study locations in northeast of Iran during 1983–2008.

Birjand		Bojnord		Mashhad		Sabzevar		Torbat heydarieh	
Indices	r	Indices	r	Indices	r	Indices	r	Indices	r
ETC7	−0.564**	ETC2	0.154	ETC7	−0.109	ETC7	−0.303	ETC7	−0.157
ETC2	0.227	ETC3	−0.216	AET7	−0.008	D7	−0.124	AET4	0.315
AET6	0.089	AET3	0.270	AET6	0.112	ETC2	0.114	S3	0.147
PET6	−0.147	AET5	0.169	AET5	−0.172	PET6	0.190	S6	−0.083
AET5	0.009	PET6	−0.202	AET3	0.347	AET5	−0.126	P3	0.011
AET7	−0.003	AET7	−0.141	P6	0.596**	AET4	0.232	P4	0.364
P6	0.358	P7	0.311	P4	0.275	P6	0.141	P6	0.363
ETC6	−0.381	P2	−0.248	P3	0.374	P5	0.026	AET7	0.076

** Correlation is significant at the 0.01 level (2-tailed).

location, four extreme points have been chosen representing two years (1994 and 2003) with highest PUE (6.5 and 7.3) and two years (1990 and 1998) with lowest values of PUE (both around 1.9). In two low cases very high amount of precipitation occurred during the whole crop growth stages but precipitation was low during heading and flowering stages (Fig. 3). In the two years with high PUE, precipitation was high during heading and flowering crop growth stages however the total precipitation during the whole crop season was low. In general precipitation plays an effective and strong role on yield formation during the two above mentioned crop growth stages. Water stress during heading and flowering growth stages is highly detrimental to final crop yield. In other locations, although the precipitation was low but due to low yield, the amount of calculated PUE was small.

Study results showed that Bojnord had also the highest WUE over the study period. Similar to PUE analysis, four extreme points have been chosen among which two years (1998–99 and 2005–6) showed the lowest WUE (0.4 and 0.6) and two years (1994–95 and 2003–4) showed the highest values (1.9 and 1.8) of WUE. The years with low WUE, showed high reference evapotranspiration during the tillering stage and high tillering in turn can have negative effects on the final yield, but this was more balanced in the years with high WUE. Generally the PUE provides more information and helps to interpret the relationship between total amounts of precipitation and the final yield.

4. Conclusion

Water shortage is the main limiting factor for crop production in arid and semi-arid regions. This condition imposes an enormous pressure on dryland farming systems to use precipitation and nutrients more efficiently. This pressure will be more significant under higher temperature and variability of precipitation patterns in dry areas. Variation of climatic conditions such as hot and dry growing season will cause severe loss of water and can detrimentally affect crop yields. This study examined the modes of variation of six climatic indices during seven phenological stages of rainfed wheat in semi-arid regions of northeast of Iran during 1983–2008. The results showed that the temporal distribution of precipitation during crop phenological stages was variable and it was approximately similar to the temporal pattern of actual evapotranspiration (AET). However the temporal pattern of rainfall variation did not show significant coordination with temporal pattern of crop evapotranspiration (ETC) or crop water demand. The highest precipitation occurred during the tillering stage of wheat crop growth which is not the most sensitive crop growth stage to water deficit. It shows that precipitation in study area has usually occurred when the crop water requirement is low. For example in Bojnord with highest yield among the study locations, significant precipitation occurred during the maturity stage while this stage is the final stage of growth and therefore precipitation at this period is not required and even can have negative effects on final yield. In addition the principle component analysis showed the sensitivity of wheat to precipitation and actual crop evapotranspiration especially during grain filling period. Therefore it seems that, precipitation timing pattern and evapotranspiration (AET and ETC) are effective limiting factors for rainfed wheat yield in the northeast of Iran and it is essential to establish the balance of water supply and demand systems in this area. The results of this research can be used to enhance understanding of the crop–climate relationships at different crop development stages. This study results can be used in regional yield forecasting and in the projection of climate change impacts on crop production as well.

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