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ORIGINAL ARTICLE

Susceptibility Assessment of Winter Wheat, Barley and Rapeseed to Drought Using Generalized Estimating Equations and Cross-Correlation Function

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Abstract
Due to the impact of drought on crop yield, the aim of this research is the susceptibility assessment of winter wheat, barley and rapeseed species to drought using Generalized Estimating Equations (GEE) and Cross-Correlation Function (CCF). For this objective, the climatic data of 10 synoptic stations in Iran from 1968 to 2017 (i.e., 50 years) were used. Then, the AquaCrop model was adopted to simulate annual yield (A_y) of the above-mentioned species. Also, the standardized precipitation evapotranspiration index (SPEI) was applied to assess drought conditions in selected constant and progressively increasing reference time periods, including 1-month, 3-month, 6-month and 12-month time scales (27 reference time periods) starting in October. For evaluating the accuracy of the GEE model, the correlation coefficients (CC) between simulated and predicted annual yields in selected species through the AquaCrop model and GEE model were used, respectively. The accuracy test of the GEE model showed that the CC between simulated and predicted annual yield of barley almost in all stations and all-time scales were significant at 0.01 level. Only in Birjand and Kerman stations the CC between simulated and predicted annual yield were significant at 0.05 level in 3.7% and 66.67% of time scales, respectively. Based on the GEE and CCF models in all stations, the susceptibility of rapeseed to drought was more than that of wheat, and the susceptibility of wheat was more than that of barley.

Keywords Rapeseed · Winter wheat · Barley · SPEI · GEE · Cross-correlation function

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1 Introduction

Over the last few decades, meteorological droughts have been one of the natural disasters that have had negative impacts on agriculture productions and food security in the world, especially in arid and semi-arid regions. The drought, which can occur in various regions with any climates, has different impacts on various sections, especially those with greater dependency on water; for example: environment section, rangelands, surface and sub-surface water resources, agricultural productions especially rain-fed farming section, etc. (Hamal et al. 2020; Iqbal et al. 2020; Schierhorn et al. 2020; Otkin et al. 2019; Wine 2019; Zarei 2018). Therefore, it is important to evaluate the drought conditions in different regions properly and determine the severity of various droughts. The Standardized Precipitation Evapotranspiration Index (SPEI), introduced by Vicente-Serrano et al. (2010), is one of the newest and the most applied indices used to monitor drought conditions in different time scales (Danandeh Mehr et al. 2020; Shen et al. 2019). There have been a lot of studies (e.g., Ayantobo et al. 2019; Bhuyan-Erhardt et al. 2019; Khoshoei et al. 2019; Wable et al. 2019; Wang et al. 2019a) conducted on drought around the world by using the SPEI.

Li et al. (2019) compared the Standardized Precipitation Index (SPI), SPEI based on Penman-Monteith (SPEI-PM) and SPEI based on Thornthwaite (SPEI-TH) by using data series of 35 stations in Yangtze River Basin during 1959–2017. The results indicated that the SPEI-PM was the best index to assess drought conditions. Wable et al. (2019) compared five drought indices in River Basin (Western India) with semi-arid climate conditions and found that the SPEI 9-month was the most suitable index for evaluating the drought conditions. Tian et al. (2018) evaluated 6 drought indices to assess agricultural drought in the south-central United States; the study revealed that there is a relatively higher CC between the SPEI and Z-score and all the crop yields. Labudová et al. (2017) compared the SPI and SPEI indices to evaluate drought effect on crop yield in the East Slovakian. The results showed that there is the highest CC between 3-monthly SPEI and maize yield.

On the other hand, regarding the drought effects on the annual yield of crops, many researchers have tried to evaluate the sensitivity of various plant species to drought (e.g., Chen et al. 2020; Huang et al. 2020; Gao et al. 2019; Leng and Hall 2019; Meise et al. 2019; Peña-Gallardo et al. 2019; Peña-Gallardo et al. 2018). Peña-Gallardo et al. (2019) evaluated the response of the annual crop yield to drought (based on SPEI) in 5 main dryland cultivations in the United States. The results showed that the CC between drought and crop yield in regions with humid climate conditions was less than other regions. On the other hand, the winter wheat responded to drought at medium to long SPEI time-scales, while soybean and corn responded to short or long drought time-scales. Samarah (2005) evaluated the drought effects on growth and yield of barley. The results showed that drought stress was detrimental to grain yield, regardless of the stress severity. Marček et al. (2019) assessed the metabolic response to drought in six winter wheat genotypes.

Chen et al. (2018) assessed the drought and flood effects on crop production in China during 1949–2015 using the Bayesian hierarchical model. The results showed a significant reduction in the grain yields in 90.32% of provinces of the study region. Páscoa et al. (2017) evaluated the drought effects on wheat yield in the Iberian Peninsula during 1929–2012. They found a strong control on wheat yield in May and June. Li et al. (2018) evaluated the response of vegetation to drought in different time scales in Mongolia plateau. Results indicated that vegetation in steppe regions is more sensitive to shorter time-scales of droughts, while it is more sensitive to longer drought time-scales in the forest regions. Zhao et al. (2019) assessed the drought effects on vegetation dynamics in China's

Loess Plateau. The study showed that the severe and extreme drought (SPEI<−1.5) has reduced the normalized difference vegetation index (NDVI) of the region studied in 2001 and 2005. Jalil et al. (2020) revealed that the AquaCrop model was able to accurately simulate the water productivity of crop in Kabul. Using the GEE and CCF models in hydrological studies has been less considered. Zarei et al. (2020) and Chakraborty (2020) are some of the researchers that used the GEE and CCF models.

This study aims at evaluating the susceptibility of winter wheat, barley and rapeseed to drought because of the following reasons: a) the necessity of sustainably feeding the rapidly growing population; b) the important role of wheat, barley and rapeseed in food security of humans and livestock worldwide; c) the occurrence of successive droughts and the increase in their intensity affected by human-activities-related changes; and d) the impacts of drought occurrence on the yield of wheat, barley and rapeseed. To accurately and comprehensively achieve this aim, the impact of drought on all plant growth periods (in 27 different time periods) was investigated using two new statistical models (in agricultural science) including GEE and CCF models.

2 Material and Methods

2.1 Study Region

The study region corresponds to Iran covering an area about 168 million hectares extending from 25.56° to 39.77°N and 44.02° to 63.36°E (Fig. 1). The average height of Iran varies from less than −10 m at Caspian Sea coasts to about 5333 m above sea level at the Damavand Mountain. Based on Modified De-Martonne index, the climate conditions of Iran vary from hyper-humid to hyper-arid in the northwest (such as Bandar Anzali) and central regions (such as Yazd) of Iran, respectively (Zarei and Moghimi 2019b; Zarei 2018). The statistical population of the study included 10 synoptic stations with the suitable spatial distribution and adequate time duration of meteorological data series with hyper-arid (Esfahan) to semi-arid (Arak, Ghazvin, Sanandaj and Shiraz) climate conditions during 1968–2017. Based on the data collected from the selected stations, the mean of monthly precipitation of the study area varies from 10.75 mm at Esfahan station to 36.49 mm at Sanandaj station, while the mean of the monthly potential evapotranspiration of the study area varies from 115.92 mm at Ghazvin station to 171.39 mm at Sabzevar station. Geographic location and climatic properties of the selected stations are presented in Table 1.

2.2 Methods

2.2.1 Data Collection and Selection of the Appropriate Time Period

In this research, climatic data series of 10 stations including Arak, Brjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran synoptic stations from 1968 to 2017, prepared by the Iran Meteorological Organization (IMO), were used to calculate values of drought index in different time scales (SPEI index), and simulate the A_y of winter wheat, barley and rapeseed. To estimate missing values and to evaluate the homogeneity of data series in all stations, the multiple imputation and Mockus methods were adopted, respectively (Rezazadeh Jodi and Sattari 2016). The appropriate time periods were selected in accordance with planting to harvesting time of winter

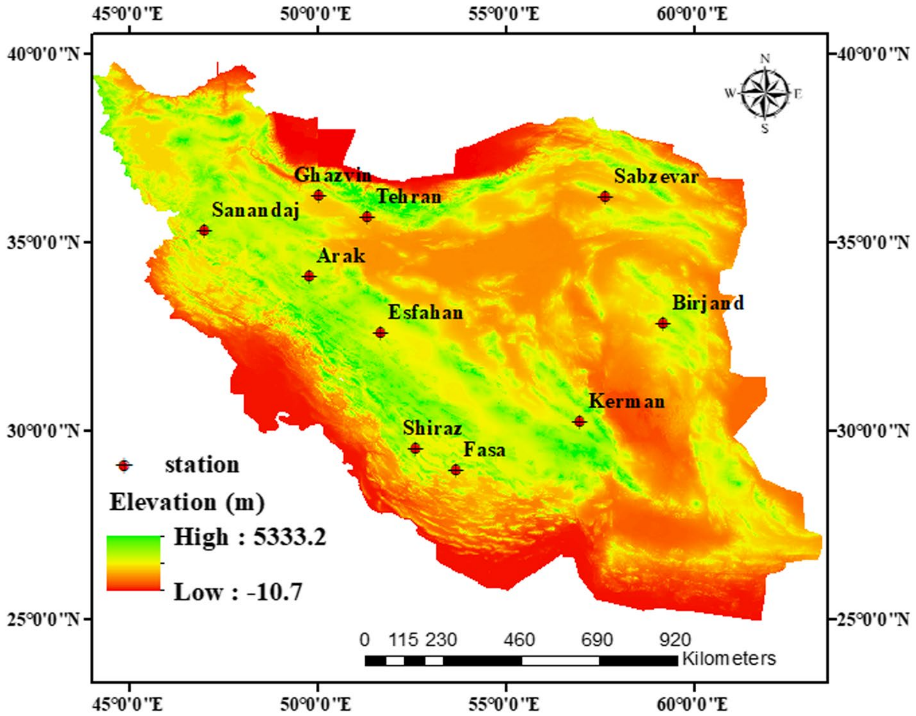

Fig. 1 Location of selected stations in the study area (Iran)

wheat, barley and rapeseed species at the selected stations, according to the difference in planting to harvesting time in selected species and selected station. Accordingly, constant and progressively increasing appropriate time periods include the following periods: 1-month (11 time periods), 3-month (9 time periods), 6-month (6 time periods), and 12-month (1 time period). These time periods started in October (Zarei et al. 2019; Tigkas et al. 2018; Tigkas et al. 2016) and are presented in detail in Table 5.

2.2.2 SPEI Calculation

To calculate the SPEI, first, the differences (*Di*) between the rainfall (R_i) and potential evapotranspiration or PET (to calculate PET the FAO Penman-Monteith or FAO-56 was used) for month *i* were calculated and aggregated at different time scales (D^k):

$$Di = R_i - PET_i \quad (1)$$

$$D^k = \sum_{i=0}^{k-1} R_{n-i} - PET_{n-i} \quad (2)$$

then based on the L-moment procedure, the probability density function of a three-parameter log-logistic distribution was applied to take into account the negative values of D^k:

Table 1 Characteristics of the selected meteorological synoptic stations

Stations name	Latitude (UTM)	Longitude (UTM)*	Elevation from free sea level (m)	Rainfall (mm/month)	Monthly average temperature (C)	Average PET (mm/month) **	Climate Condition***
Arak	3,773,931	386,233	1708	26.93	13.94	116.35	SA
Birjand	3,638,652	705,845	1490	13.34	16.46	161.31	A
Esfahan	3,608,987	562,546	1550	10.75	16.56	133.18	HA
Fasa	3,207,258	761,492	1288	24.21	19.43	143.96	A
Ghazvin	4,012,097	414,647	1279	26.74	13.97	115.92	SA
Kerman	3,346,487	496,792	1753	11.34	16.02	165.03	A
Sabzevar	4,006,368	564,427	976	16.09	17.87	171.39	A
Sanandaj	3,911,843	681,773	1373	36.49	13.74	121.99	SA
Shiraz	3,268,143	655,042	1484	26.57	18.11	148.55	SA
Tehran	3,948,873	528,655	1190	19.87	17.78	148.83	A

*Geographic zone number (GZN) of Sanandaj station is 38, for Arak, Birjand, Esfahan, Fasa, Ghazvin and Shiraz stations GZN is 39, and for Kerman and Sabzevar stations GZN is 40. **PET is potential evapotranspiration. ***To assess climate conditions Modified De Martonne index (MDM) were used (De Martonne 1926; Zarei et al. 2019), if MDM index ≤ 5 climate condition is Hyper-Arid (HA), climate condition was classified Arid if $5 < \text{MDM index} \leq 10$, and climate condition was classified Semi-Arid if $10 < \text{MDM index} \leq 20$

$$F(x) = \frac{\lambda}{k}\left(\frac{x-\mu}{k}\right)^{\lambda-1}\left[\left(1+\frac{x-\mu}{k}\right)^{\lambda}\right]^{-2} \tag{3}$$

where k, λ and μ are scale parameters.

Finally, to compute the original SPEI, the calculated values of F(x) were converted into corresponding Z-standardized normal values (Vicente-Serrano et al. 2010). Drought classes based on SPEI are presented in Table 2. For Further information about SPEI, one can refer to some studies (e.g., Barbosa et al. 2019; Li et al. 2019; Wang et al. 2019b; Zarei and Moghimi 2019a).

2.2.3 Simulation Annual Yield (A_y) of Winter Wheat, Barley and Rapeseed

The AquaCrop model was employed to simulate A_y of winter wheat, barley and rapeseed in all stations during 50 years (from 1968 to 2017). The AquaCrop model is one of the most applied models to simulate crop yield in different regions because the AquaCrop model needs low input data and has a user-friendly structure (Zarei et al. 2019). In this research, the climatic parameters in each station (such as precipitation, temperature and potential evapotranspiration) and the AquaCrop model which was calibrated and validated for winter wheat, Barley and rapeseed species by Shirshahi et al. (2018), Ramezani et al. (2019) and Mousavizadeh et al. (2016) were used in order to simulate the A_y of the mentioned species in each station, respectively.

2.2.4 Statistical Analysis

Generalized Estimating Equations (GEE) To model and predict the response variable (A_y of winter wheat, barley and rapeseed) based on the predictive variables (SPEI in different time scales), we have a panel dataset. Fixed or random effects techniques or generalized estimating equations (GEE), in abbreviation are suggested to analyze the panel dataset. Based on the nature of samples and also favorable study's focus, each of these approaches has particular privileges (Hu et al. 1998). The GEE techniques have many privileges, especially this approach intends robust estimations for the regression parameters when there is a high correlation between repeated measurements (Ballinger 2004; Ghisletta and Spini 2004; Hu et al. 1998). This advantage guides us to apply the GEE technique in the present study. The simple GEE formula is written by:

$$Y_t = \beta_0 + \beta_1 X_t + \epsilon_t \tag{4}$$

Table 2 Drought classification based on SPEI index (Vicente-Serrano et al. 2010; Zarei et al. 2019)

Class	SPEI values
Extremely Wet (EW)	SPEI index ≥ 2
Very Wet (VW)	$1.5 \leq$ SPEI index <2
Moderately Wet (MW)	$1 \leq$ SPEI index <1.5
Normal (N)	$-1 <$ SPEI index <1
Moderately Dry (MD)	$-1.5 <$ SPEI index ≤ -1
Severely Dry (SD)	$-2 <$ SPEI index ≤ -1.5
Extremely Dry (ED)	SPEI index ≤ -2

where β_0 and β_1 are regression parameters (coefficients) and ϵ_t is a zero-mean random variable.

To create this predictive regression model, the GEE technique uses a link function which depends on the distribution of the response variable (Y_t). In this research, because the normality assumption was satisfied for Y_t, the non-transforming identity link function was used. Also, GEE needs a working correlation matrix; because of the significant Pearson's correlation between the current and previous samples, the first-order autoregressive, AR (1), was considered as the working correlation matrix. The GEE method estimates the model parameters through an iterative procedure that optimizes the fit of the model to the dataset.

Ability Assessment of the GEE Model In the GEE model, the absolute values of Beta coefficients ($|B|$) between SPEI in different time scales and A_y of different species were utilized to evaluate the relationship between drought and A_y of selected species in each station. It is shown that the higher the values of $|B|$ coefficient, the higher the impact of SPEI on A_y. In addition, in this research, the correlation coefficients (CC) between simulated A_y using the AquaCrop model and predicted A_y using GEE methods, were used to assess the ability of the GEE model in predicting A_y of selected species based on SPEI in different time scales.

Cross-Correlation Function (CCF) The CCF is a measure that can be applied as a rate of similarity between two functions or datasets (Shumway and Stoffer 2017; Venables and Ripley 2002). Let f and g be two continuous functions; then the CCF in a given lag τ is defined by:

$$(f * g)(\tau) = \int_{-\infty}^{\infty} f^*(t)g(t+\tau)dt \tag{5}$$

where f^* denotes the complex conjugate of f, τ is any arbitrary integer and t is time.

In the discrete case, the cross-correlation is defined as

$$(f * g)(\tau) = \sum_{t=-\infty}^{\infty} f^*(t)g(t+\tau) \tag{6}$$

As it can be observed, the cross-correlation measures the similarity of $f(t)$ and $g(t+\tau)$. Let (X_t, Y_t) represent a pair of stationary time series. The mean (μ_X) and the standard deviation (σ_X) of the time series X_t are defined by

$$\mu_X = E(X_t) = \int_{-\infty}^{\infty} x f_X(x)dx, \tag{7}$$

and

$$\sigma_X^2 = E(X_t - \mu_X)^2 = \int_{-\infty}^{\infty} (x - \mu_X)^2 f_X(x)dx, \tag{8}$$

where $f_X(x)$ is the density function of the time series X_t at point x.

Similarly, the mean (μ_Y) and the standard deviation (σ_Y) of the time series Y_t are defined by

$$\mu_Y = E(Y_t) = \int_{-\infty}^{\infty} y f_Y(y)dy, \tag{9}$$

and

$$\sigma_Y^2 = E\left(Y_t - \mu_Y\right)^2 = \int_{-\infty}^{\infty} \left(y - \mu_Y\right)^2 f_Y(y)dy, \tag{10}$$

where $f_Y(y)$ is the density function of the time series Y_t at point y.

In addition, the covariance function of the time series (X_t, Y_t) in lag τ is defined by

$$\gamma_{X,Y}(\tau) = E\left[\left(X_t - \mu_X\right)\left(Y_{t+\tau} - \mu_Y\right)\right] = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \left(X_t - \mu_X\right)\left(Y_{t+\tau} - \mu_Y\right) f_{X,Y}(x,y)dxdy, \tag{11}$$

where $f_{X,\,Y}(x, y)$ is the density function of the time series (X_t, Y_t) at point (x, y).

Then, the CCF of X_t and Y_t in lag τ is given as:

$$\rho_{X,Y}(\tau)\rho_{X,Y}(\tau) = \frac{\gamma_{X,Y}(\tau)}{\sigma_X\sigma_y} \tag{12}$$

The above-mentioned Eq. (12) is the cross-covariance function, and μ and σ are the mean and standard deviation of the time series, respectively. The CCF of two stationary processes can be estimated by sample cross-correlation function given as

$$\hat{\rho}_{X,Y}(\tau) = \frac{\hat{\gamma}_{X,Y}(\tau)}{S_X S_Y} \tag{13}$$

where

$$\overline{X} = \frac{1}{n}\sum_{t=1}^{n} X_t, \tag{14}$$

$$\overline{Y} = \frac{1}{n}\sum_{t=1}^{n} Y_t, \tag{15}$$

$$S_X^2 = \frac{1}{n-1}\sum_{t=1}^{n}\left(X_t - \overline{X}\right)^2, \tag{16}$$

$$S_Y^2 = \frac{1}{n-1}\sum_{t=1}^{n}\left(Y_t - \overline{Y}\right)^2, \tag{17}$$

and

$$\hat{\gamma}_{X,Y}(\tau) = \frac{1}{n}\sum_{t=1}^{n-|\tau|}\left(X_t - \overline{X}\right)\left(Y_{t+\tau} - \overline{Y}\right) \tag{18}$$

The above-mentioned Eq. (18) is the sample cross-covariance function and $s_X$and s_Y are the sample standard deviation of the process. The CCF is a useful tool to determine the rate of similarity (which can be between −1 to +1) and the time delay between two processes.

Table 3 Years with the highest (The wettest year (and the lowest) The driest year (values of SPEI index in annual time scale in selected stations

Station	The highest values of SPEI index		The lowest values of SPEI index	
	SPEI value	Year	SPEI value	Year
Arak	2.25	1969	−3.21	1973
Birjand	2.09	2002	−2.10	1980
Esfahan	1.95	1996	−2.00	2013
Fasa	2.00	1995	−1.93	173
Ghazvin	1.80	1996	−2.23	1973
Kerman	2.07	1984	−2.24	1969
Sabzevar	2.39	2015	−1.97	2008
Sanandaj	1.87	1986	−2.19	1999
Shiraz	2.25	1992	−2.09	1983
Tehran	2.03	1996	−2.20	2014

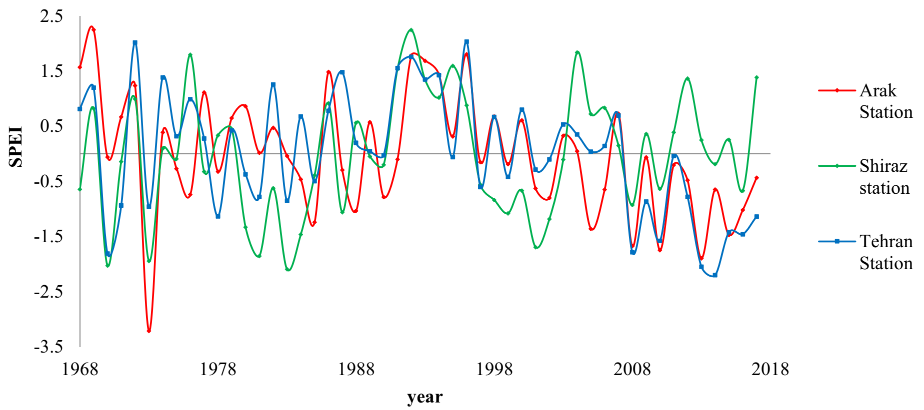

Fig. 2 Calculated 12-month SPEI (October to September) in Arak, Shiraz and Tehran stations

3 Results and Discussion

3.1 The Calculated SPEI

The results of the calculated SPEI showed that the normal class of drought severity (with SPEI between −1 to 1) had the highest frequency at all stations and all-time scales. Results showed that during 1968–2017 the highest values of the 12-month SPEI at Arak, Brjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations had occurred in 1969, 2002, 1996, 1995, 1996, 1984, 2015, 1986, 1992 and 1996, respectively, and the lowest values of the 12-month SPEI at Arak, Brjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations had occurred in 1973, 1980, 2013, 1973, 1973, 1969, 2008, 1999, 1983 and 2014 respectively (Table 3 and Fig. 2).

3.2 The Simulated Annual Yield (A_y) of Winter Wheat, Barley and Rapeseed

For different species, different results were obtained which are presented in the following. The results of simulated A_y in winter wheat using the AquaCrop model showed that the mean of simulated A_y at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations were 0.40, 0.55, 0.31, 2.37, 0.61, 0.25, 0.66, 0.67, 1.79 and 0.79, respectively (Fig. 3). In barley, the mean of simulated A_y at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations were 0.74, 0.05, 0.14, 0.59, 0.58, 0.05, 0.26, 0.59, 0.24 and 0.56, respectively (Fig. 4). In rapeseed, the mean of simulated A_y at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations were 0.79, 0.66, 0.35, 3.46, 1.2, 0.17, 0.82, 1.36, 2.95 and 1.34, respectively (Fig. 5). Some properties of simulated A_y in mentioned species using the AquaCrop model from 1968 to 2017 are presented in Table 4.

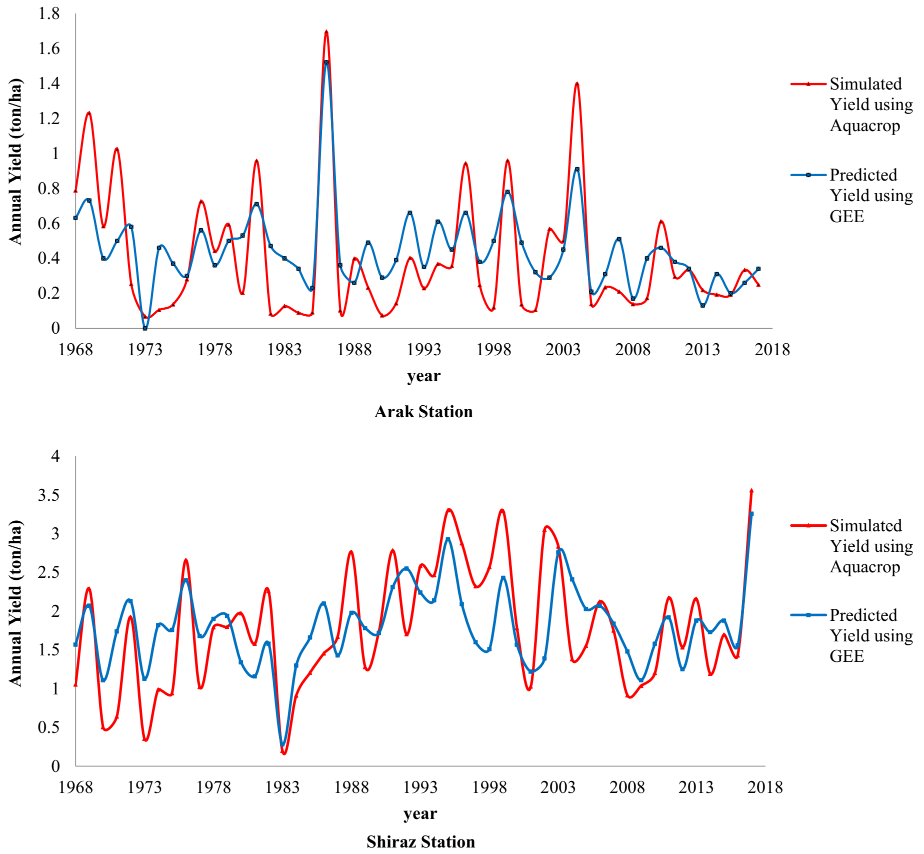

Fig. 3 Simulated and predicted annual yield of winter wheat using AquaCrop model and GEE method in Arak and Shiraz stations

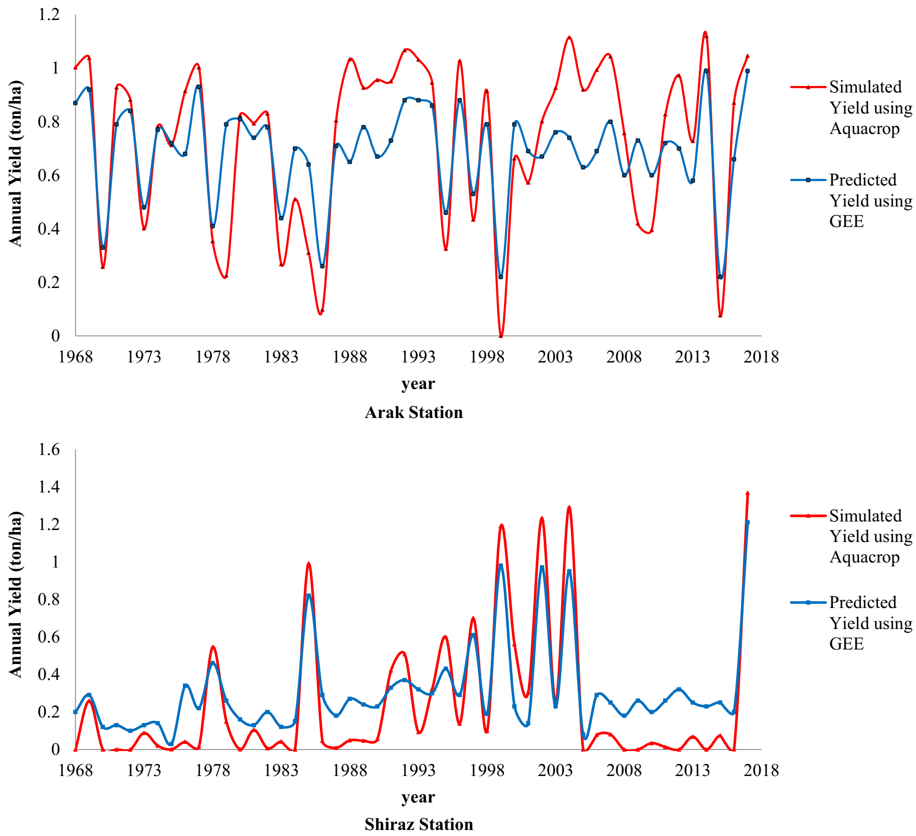

Fig. 4 Simulated and predicted annual yield of barley using AquaCrop model and GEE method in Arak and Shiraz stations

3.3 Susceptibility Test of Winter Wheat, Barley and Rapeseed to Drought Using GEE

The results of the susceptibility test of winter wheat, barley and rapeseed to drought using the GEE model showed that at all stations, rapeseed with the highest values of Beta coefficients (|*B*|) was the most sensitive species, and barley with the lowest values of Beta coefficients (|*B*|) was the most resistant species to drought, respectively. The results also showed that the rapeseed had the highest values of |*B*| coefficients at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations in 81.48%, 100%, 92.59%, 96.30%, 85.18%, 62.96%, 96.30%, 81.48%, 85.18% and 92.59% of reference periods, respectively. However, barley had the lowest values of |*B*| coefficients at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations in 62.96%, 100%, 66.67%, 96.30%, 55.56%, 81.48%, 92.59%, 81.48%, 81.48% and 85.18% of reference periods, respectively. The general results of Tables 5, 6 and 7 show that the level of the absolute values of B coefficients for rapeseed (Table 7) is higher than wheat (Table 5), and for wheat it is higher than barley (Table 6), which indicates that barley is less susceptible to drought. The results showed that at all stations winter wheat had moderate drought sensitivity compared to barley and rapeseed. In other words, among the

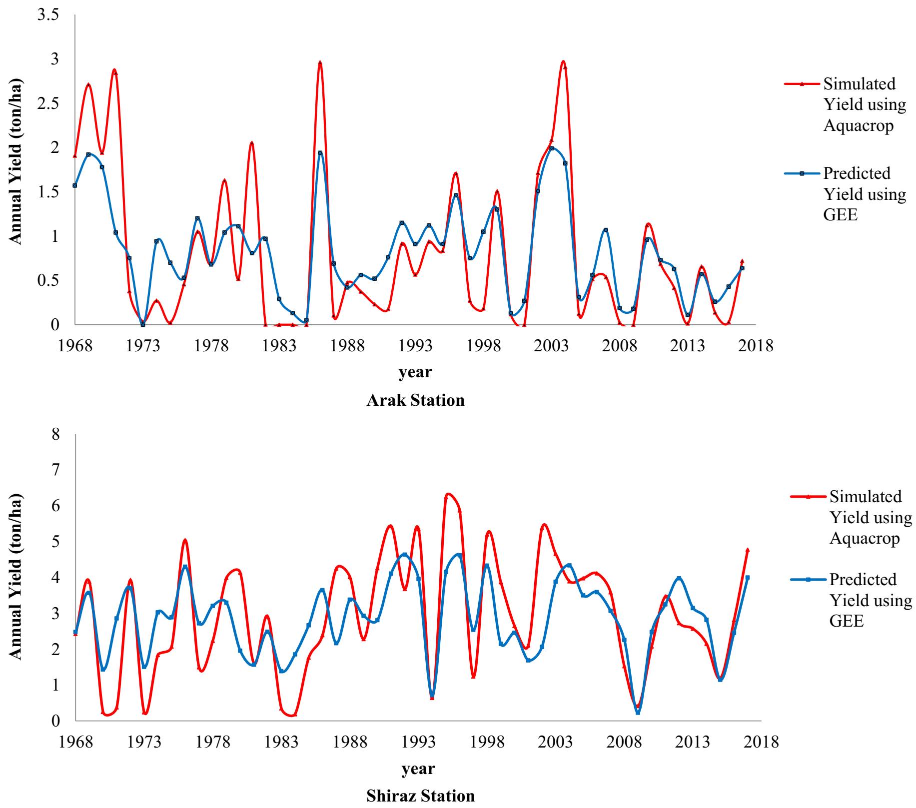

Fig. 5 Simulated and predicted annual yield of rapeseed using AquaCrop model and GEE method in Arak and Shiraz stations

selected species, the susceptibility of rapeseed to drought was more than wheat and the susceptibility of wheat was more than barley. The reasons of these results can be shorter growth period in barley than winter wheat and rapeseed, less evapotranspiration in barley than winter wheat and rapeseed and the larger canopy cover in rapeseed.

3.4 Ability Assessment of the GEE Model to Predict A_y

The correlation coefficients (CC) between simulated and predicted A_y of the winter wheat, barley and rapeseed using the AquaCrop model and GEE method (respectively) indicated that in winter wheat the CC between simulated and predicted A_y at all stations and all-time scales were significant at 0.01 level (Table 8). Table 8 showed that the average of CC was 0.771, 0.860, 0.815, 0.949, 0.787, 0.781, 0.825, 0.755, 0.926 and 0.841, at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations, respectively. In barley, the CC between simulated and predicted A_y were significant at 0.01 level at Arak, Esfahan, Fasa, Ghazvin, Sabzevar, Sanandaj, Shiraz and Tehran stations in all-time scales (Table 9). The CC in 33.33% and 96.30% of reference periods were significant at 0.01 level, respectively and in 66.67% and 3.7% of reference periods were significant at 0.05 level at Kerman and Birjand stations, respectively. Table 9 showed that the mean of

Table 4 Some properties of simulated A_y in winter wheat, barley and rapeseed using AquaCrop Model from 1968 to 2017

Specie	Statistical Parameter	Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Tehran
Winter wheat	Mean	0.401	0.551	0.309	2.366	0.610	0.255	0.657	0.671	1.786	0.789
	Minimum	0.067	0.094	0.068	0.486	0.056	0.048	0.071	0.042	0.197	0.128
	Maximum	1.696	2.116	1.237	4.258	2.652	1.136	2.132	2.833	3.559	2.382
	Skewness	1.706	1.491	2.106	−0.017	1.523	1.964	1.037	1.516	0.235	1.069
	Kurtosis	2.654	2.580	5.270	−1.100	3.221	4.666	0.236	1.940	−0.558	0.686
Barley	Mean	0.736	0.046	0.135	0.591	0.576	0.047	0.260	0.590	0.238	0.556
	Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	Maximum	1.120	0.549	1.070	1.331	1.116	0.777	1.216	1.155	1.368	1.272
	Skewness	−0.845	3.266	2.288	0.058	−0.197	4.311	1.411	−0.266	1.907	0.178
	Kurtosis	−0.504	10.722	5.270	−1.694	−1.624	20.808	0.904	−1.501	2.676	−1.517
Rapeseed	Mean	0.791	0.662	0.346	3.463	1.198	0.165	0.816	1.357	2.951	1.341
	Minimum	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.003	0.191	0.002
	Maximum	2.961	3.308	1.483	7.325	4.480	1.310	3.541	5.460	6.241	4.610
	Skewness	1.205	1.555	1.436	0.068	0.929	2.391	1.113	1.215	0.007	0.953
	Kurtosis	0.420	2.200	1.261	−1.180	0.173	5.333	0.066	1.123	−0.911	0.496

Table 5 |*B*| coefficients between simulated annual yield of winter wheat using AquaCrop model and SPEI using GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Tehran
1 month	Oct	0.019	0.176	0.038	0.588	0.268	0.250	0.190	0.081	0.041	0.338
	Nov	0.037	0.136	0.016	0.135	0.096	0.043	0.115	0.056	0.063	0.146
	Dec	0.062	0.025	0.024	0.090	0.035	0.031	0.093	0.176	0.051	0.112
	Jan	0.023	0.107	0.005	0.440	0.093	0.018	0.003	0.066	0.046	0.065
	Feb	0.002	0.236	0.000	0.686	0.005	0.013	0.065	0.013	0.135	0.049
	Mar	0.053	0.233	0.118	0.705	0.034	0.095	0.210	0.076	0.475	0.006
	Apr	0.192	0.154	0.041	0.159	0.112	0.059	0.322	0.032	0.378	0.274
	May	0.147	0.163	0.021	0.292	0.321	0.016	0.169	0.385	0.151	0.166
	Jun	0.122	0.156	0.019	0.470	0.080	0.008	0.187	0.255	0.054	0.125
	Jul	0.115	0.227	0.064	0.492	0.073	0.039	0.204	0.245	0.070	0.077
	Aug	0.117	0.334	0.046	0.507	0.052	0.071	0.213	0.212	0.009	0.106
3 months	Oct - Dec	0.028	0.234	0.010	0.265	0.099	0.139	0.182	0.227	0.318	0.105
	Nov - Jan	0.011	0.127	0.005	0.389	0.032	0.035	0.165	0.085	0.007	0.076
	Dec- Feb	0.008	0.113	0.013	0.635	0.017	0.026	0.073	0.083	0.112	0.021
	Jan - Mar	0.044	0.195	0.075	0.913	0.006	0.081	0.156	0.018	0.310	0.007
	Feb- Apr	0.142	0.293	0.085	0.783	0.088	0.096	0.317	0.052	0.526	0.206
	Mar- May	0.186	0.281	0.082	0.640	0.264	0.077	0.328	0.255	0.520	0.240
	Apr- Jun	0.196	0.240	0.036	0.444	0.267	0.025	0.284	0.328	0.308	0.249
	May–July	0.152	0.214	0.048	0.490	0.231	0.018	0.208	0.361	0.129	0.246
	Jun- Aug	0.121	0.222	0.053	0.488	0.084	0.047	0.223	0.250	0.065	0.162

Table 5 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.018	0.235	0.064	0.777	0.088	0.063	0.203	0.214	0.109	0.137
	Nov- Apr	0.115	0.266	0.062	0.744	0.096	0.090	0.312	0.084	0.407	0.113
	Dec- May	0.142	0.255	0.055	0.740	0.215	0.071	0.303	0.216	0.426	0.197
	Jan- Jun	0.161	0.258	0.065	0.874	0.207	0.063	0.278	0.246	0.410	0.242
	Feb- July	0.165	0.293	0.076	0.785	0.217	0.071	0.285	0.305	0.490	0.219
	Mar- Aug	0.182	0.290	0.090	0.654	0.212	0.080	0.291	0.313	0.415	0.221
12 months	Oct- Sep	0.143	0.266	0.075	0.752	0.215	0.060	0.258	0.320	0.285	0.217

Table 6 |*B*| coefficients between simulated annual yield of barley using AquaCrop model and SPEI using GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.072	0.011	0.007	0.046	0.008	0.060	0.108	0.008	0.207	0.058
	Nov	0.026	0.014	0.038	0.019	0.024	0.003	0.121	0.028	0.019	0.014
	Dec	0.073	0.002	0.009	0.048	0.044	0.019	0.046	0.047	0.015	0.025
	Jan	0.102	0.019	0.061	0.190	0.029	0.021	0.055	0.004	0.074	0.029
	Feb	0.102	0.002	0.052	0.043	0.137	0.043	0.030	0.048	0.082	0.009
	Mar	0.066	0.002	0.010	0.045	0.132	0.022	0.070	0.125	0.021	0.141
	Apr	0.109	0.007	0.055	0.023	0.121	0.018	0.059	0.176	0.024	0.041
	May	0.026	0.002	0.085	0.076	0.032	0.015	0.027	0.014	0.058	0.065
	Jun	0.009	0.014	0.018	0.062	0.009	0.017	0.038	0.021	0.032	0.004
	Jul	0.008	0.003	0.028	0.087	0.091	0.016	0.045	0.028	0.009	0.095
	Aug	0.013	0.016	0.012	0.043	0.073	0.020	0.040	0.033	0.005	0.054
3 months	Oct - Dec	0.014	0.007	0.019	0.049	0.055	0.004	0.034	0.082	0.323	0.011
	Nov - Jan	0.034	0.008	0.018	0.133	0.052	0.006	0.070	0.052	0.060	0.066
	Dec- Feb	0.078	0.013	0.058	0.158	0.038	0.028	0.032	0.015	0.091	0.056
	Jan - Mar	0.117	0.007	0.048	0.139	0.151	0.041	0.060	0.087	0.128	0.073
	Feb- Apr	0.140	0.011	0.019	0.055	0.186	0.037	0.057	0.153	0.084	0.041
	Mar- May	0.096	0.000	0.009	0.072	0.139	0.015	0.046	0.141	0.012	0.004
	Apr- Jun	0.074	0.001	0.001	0.079	0.080	0.013	0.035	0.078	0.045	0.193
	May–July	0.011	0.003	0.007	0.085	0.052	0.001	0.032	0.005	0.039	0.050
	Jun- Aug	0.006	0.007	0.021	0.081	0.066	0.002	0.049	0.022	0.014	0.010

Table 6 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.101	0.009	0.033	0.138	0.092	0.012	0.044	0.040	0.000	0.054
	Nov- Apr	0.128	0.013	0.026	0.139	0.108	0.029	0.084	0.071	0.103	0.055
	Dec- May	0.108	0.006	0.040	0.144	0.139	0.026	0.061	0.085	0.088	0.019
	Jan- Jun	0.116	0.004	0.030	0.145	0.134	0.029	0.050	0.096	0.079	0.030
	Feb- July	0.093	0.005	0.007	0.091	0.144	0.022	0.054	0.088	0.034	0.003
	Mar- Aug	0.066	0.006	0.011	0.096	0.120	0.005	0.059	0.075	0.026	0.016
12 months	Oct- Sep	0.081	0.005	0.003	0.136	0.103	0.002	0.048	0.039	0.033	0.023

Table 7 $|B|$ coefficients between simulated annual yield of rapeseed using AquaCrop model and SPEI using GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.083	0.357	0.079	1.225	0.504	0.497	0.529	0.091	0.072	0.749
	Nov	0.030	0.292	0.056	0.002	0.277	0.052	0.430	0.102	0.137	0.350
	Dec	0.187	0.025	0.004	0.190	0.060	0.025	0.066	0.654	0.253	0.098
	Jan	0.106	0.301	0.116	1.171	0.189	0.005	0.153	0.097	0.040	0.161
	Feb	0.055	0.392	0.101	1.204	0.118	0.056	0.239	0.001	0.562	0.286
	Mar	0.161	0.338	0.176	1.190	0.130	0.137	0.507	0.094	1.083	0.306
	Apr	0.488	0.216	0.057	0.334	0.300	0.087	0.525	0.082	0.511	0.624
	May	0.343	0.328	0.000	0.466	0.719	0.034	0.272	0.900	0.326	0.281
	Jun	0.286	0.468	0.023	1.028	0.270	0.011	0.381	0.612	0.002	0.357
	Jul	0.314	0.408	0.094	0.916	0.244	0.039	0.352	0.480	0.359	0.282
	Aug	0.268	0.569	0.063	0.969	0.189	0.008	0.436	0.408	0.217	0.299
3 months	Oct - Dec	0.136	0.475	0.060	0.482	0.279	0.200	0.339	0.429	0.175	0.350
	Nov - Jan	0.002	0.252	0.081	0.869	0.106	0.027	0.321	0.153	0.098	0.089
	Dec- Feb	0.007	0.266	0.108	1.366	0.029	0.038	0.218	0.151	0.269	0.052
	Jan - Mar	0.166	0.370	0.209	1.755	0.094	0.121	0.496	0.020	0.894	0.298
	Feb- Apr	0.399	0.505	0.172	1.304	0.300	0.154	0.648	0.085	1.145	0.669
	Mar- May	0.477	0.429	0.113	1.152	0.635	0.110	0.609	0.553	0.943	0.612
	Apr- Jun	0.493	0.379	0.055	0.947	0.666	0.023	0.499	0.767	0.432	0.899
	May–July	0.377	0.371	0.079	1.059	0.582	0.001	0.376	0.845	0.263	0.541
	Jun- Aug	0.309	0.430	0.093	1.017	0.299	0.034	0.432	0.564	0.177	0.375

Table 7 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.045	0.452	0.197	1.533	0.282	0.057	0.394	0.427	0.396	0.410
	Nov- Apr	0.307	0.480	0.178	1.460	0.313	0.127	0.636	0.145	0.844	0.365
	Dec- May	0.375	0.429	0.140	1.502	0.558	0.102	0.603	0.456	0.895	0.542
	Jan- Jun	0.439	0.436	0.152	1.699	0.569	0.085	0.578	0.543	0.919	0.601
	Feb- July	0.446	0.507	0.144	1.391	0.594	0.096	0.555	0.659	1.061	0.609
	Mar- Aug	0.473	0.502	0.138	1.239	0.570	0.092	0.552	0.689	0.803	0.630
12 months	Oct- Sep	0.364	0.478	0.159	1.499	0.567	0.056	0.474	0.716	0.529	0.589

Table 8 *CC* between simulated and predicted annual yield of winter wheat using AquaCrop model and GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.737	0.835	0.808	0.945	0.772	0.770	0.802	0.718	0.914	0.839
	Nov	0.740	0.815	0.802	0.920	0.763	0.765	0.785	0.733	0.914	0.817
	Dec	0.745	0.792	0.803	0.918	0.770	0.761	0.777	0.719	0.913	0.823
	Jan	0.738	0.807	0.801	0.934	0.762	0.760	0.781	0.715	0.916	0.822
	Feb	0.737	0.862	0.801	0.957	0.763	0.811	0.817	0.720	0.945	0.820
	Mar	0.743	0.862	0.859	0.958	0.775	0.779	0.869	0.716	0.934	0.872
	Apr	0.822	0.824	0.808	0.920	0.865	0.761	0.804	0.830	0.917	0.840
	May	0.790	0.832	0.803	0.934	0.769	0.760	0.812	0.767	0.914	0.832
	Jun	0.764	0.867	0.804	0.938	0.768	0.773	0.818	0.758	0.914	0.825
	Jul	0.773	0.851	0.820	0.937	0.765	0.794	0.820	0.753	0.913	0.830
	Aug	0.769	0.868	0.811	0.943	0.775	0.783	0.802	0.756	0.917	0.830
3 months	Oct - Dec	0.738	0.814	0.801	0.924	0.763	0.766	0.802	0.721	0.913	0.825
	Nov - Jan	0.737	0.809	0.801	0.931	0.762	0.763	0.782	0.721	0.915	0.821
	Dec- Feb	0.737	0.842	0.802	0.951	0.762	0.799	0.799	0.715	0.927	0.820
	Jan - Mar	0.741	0.904	0.825	0.985	0.769	0.815	0.865	0.717	0.953	0.849
	Feb- Apr	0.783	0.895	0.833	0.969	0.831	0.798	0.875	0.767	0.953	0.861
	Mar- May	0.817	0.872	0.832	0.953	0.834	0.763	0.854	0.801	0.928	0.866
	Apr- Jun	0.831	0.858	0.807	0.936	0.819	0.761	0.820	0.819	0.916	0.841
	May–July	0.798	0.866	0.813	0.941	0.770	0.773	0.826	0.770	0.914	0.837
	Jun- Aug	0.777	0.874	0.815	0.941	0.771	0.789	0.818	0.760	0.915	0.832

Table 8 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.737	0.887	0.819	0.967	0.771	0.806	0.862	0.721	0.938	0.846
	Nov- Apr	0.768	0.879	0.818	0.964	0.807	0.791	0.859	0.752	0.940	0.859
	Dec- May	0.784	0.882	0.814	0.963	0.804	0.784	0.848	0.763	0.939	0.854
	Jan- Jun	0.798	0.910	0.820	0.983	0.810	0.790	0.853	0.788	0.951	0.856
	Feb- July	0.805	0.911	0.829	0.973	0.810	0.799	0.857	0.795	0.942	0.857
	Mar- Aug	0.823	0.895	0.839	0.957	0.813	0.782	0.842	0.802	0.928	0.866
12 months	Oct- Sep	0.790	0.895	0.827	0.968	0.801	0.798	0.836	0.779	0.932	0.857

CC coefficients in all station and all-time scales were significant at 0.01 level

Table 9 *CC* coefficients between simulated and predicted annual yield of barley using AquaCrop model and GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.928	0.382	0.508	0.773	0.818	**0.337**	0.612	0.834	0.538	0.791
	Nov	0.923	0.**330**	0.527	0.770	0.820	**0.361**	0.612	0.836	0.539	0.793
	Dec	0.927	0.370	0.508	0.772	0.819	0.369	0.615	0.833	0.564	0.791
	Jan	0.931	0.402	0.558	0.809	0.840	0.457	0.607	0.836	0.569	0.790
	Feb	0.932	0.370	0.547	0.772	0.839	**0.373**	0.625	0.851	0.540	0.816
	Mar	0.927	0.370	0.509	0.772	0.836	**0.361**	0.618	0.869	0.540	0.792
	Apr	0.934	0.374	0.482	0.770	0.819	**0.356**	0.606	0.834	0.554	0.796
	May	0.923	0.370	0.518	0.779	0.818	**0.358**	0.610	0.834	0.543	0.790
	Jun	0.923	0.370	0.512	0.775	0.829	**0.355**	0.614	0.833	0.538	0.802
	Jul	0.923	0.392	0.520	0.778	0.825	**0.369**	0.609	0.836	0.538	0.795
	Aug	0.923	0.374	0.509	0.778	0.824	**0.337**	0.608	0.840	0.494	0.790
3 months	Oct - Dec	0.923	0.376	0.512	0.773	0.821	**0.339**	0.625	0.837	0.555	0.797
	Nov - Jan	0.924	0.386	0.512	0.790	0.819	0.392	0.607	0.834	0.576	0.794
	Dec- Feb	0.928	0.374	0.553	0.797	0.845	0.456	0.618	0.842	0.612	0.797
	Jan - Mar	0.935	0.380	0.539	0.791	0.859	0.434	0.617	0.861	0.571	0.792
	Feb- Apr	0.940	0.370	0.513	0.773	0.842	**0.355**	0.613	0.858	0.538	0.790
	Mar- May	0.931	0.370	0.508	0.776	0.826	**0.350**	0.609	0.841	0.548	0.794
	Apr- Jun	0.928	0.371	0.507	0.778	0.821	**0.336**	0.608	0.833	0.546	0.790
	May–July	0.923	0.375	0.508	0.779	0.824	**0.337**	0.614	0.834	0.539	0.795
	Jun- Aug	0.923	0.378	0.515	0.779	0.830	**0.350**	0.612	0.836	0.538	0.796

Table 9 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.932	0.386	0.523	0.791	0.832	0.395	0.634	0.839	0.588	0.791
	Nov- Apr	0.937	0.374	0.517	0.791	0.841	0.387	0.620	0.842	0.574	0.791
	Dec- May	0.933	0.371	0.531	0.793	0.840	0.401	0.614	0.845	0.568	0.790
	Jan- Jun	0.935	0.372	0.521	0.795	0.844	0.374	0.616	0.843	0.544	0.791
	Feb- July	0.931	0.373	0.508	0.780	0.837	**0.339**	0.620	0.841	0.541	0.791
	Mar- Aug	0.927	0.373	0.509	0.781	0.832	**0.337**	0.614	0.835	0.544	0.791
12 months	Oct- Sep	0.929	0.376	0.507	0.792	0.833	**0.342**	0.620	0.834	0.556	0.791

Note. *CC* coefficients in stations and time scales shown with bold characters were significant at 0.05 level and in all other stations and other time scales they were significant at 0.01 level

CC was 0.929, 0.374, 0.518, 0.782, 0.831, 0.369, 0.615, 0.840, 0.552 and 0.794 at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz and Tehran stations, respectively. In rapeseed the CC between simulated and predicted A_y at all stations and all-time scales were significant at 0.01 level (Table 10). According to Table 10, the average of CC was 0.730, 0.777, 0.714, 0.899, 0.779, 0.536, 0.753, 0.776, 0.896 and 0.811 at Arak, Birjand, Esfahan, Fasa, Ghazvin, Kerman, Sabzevar, Sanandaj, Shiraz, and Tehran stations, respectively. Therefore, it can be concluded that the GEE model was highly capable of predicting A_y at all stations and all under-evaluated species.

3.5 Susceptibility Test of Winter Wheat, Barley and Rapeseed to Drought Using CCF

According to the result of susceptibility test of winter wheat, barley and rapeseed to drought using CCF method at Arak, Birjand, Esfahan, Ghazvin, Sabzevar, Sanandaj, Shiraz and Tehran stations, it can be concluded that rapeseed with the highest values of $|CCF|$ between simulated A_y using the AquaCrop model and SPEI in more selected time scales was the most sensitive species to drought. In addition, barley with the lowest values of $|CCF|$ in more selected time scales was the most resistant species to drought (Tables 11, 12 and 13). The results indicated that at Arak, Birjand, Esfahan, Ghazvin, Sabzevar, Sanandaj, Shiraz and Tehran stations in 14 out of 27, 15 out of 27, 16 out of 27, 16 out of 27, 22 out of 27, 14 out of 27, 17 out of 27and 22 out of 27 of reference periods, respectively, rapeseed had the highest values of $|CCF|$ and in 15 out of 27, 27 out of 27, 19 out of 27, 15 out of 27, 25 out of 27, 20 out of 27, 21 out of 27and 23 out of 27 of reference periods, respectively, barley had the lowest values of $|CCF|$. Winter wheat with the highest values of $|CCF|$ in more selected time scales was the most sensitive species to drought, and barley with the lowest values of $|CCF|$ in more selected time scales was the most resistant species to drought at Fasa and Kerman stations (Tables 11, 12 and 13). The results indicated that winter wheat had the highest values of $|CCF|$ in 17 out of 27 and 14 out of 27 of reference periods, and barley had the lowest values of $|CCF|$ in 26 out of 27 and 20 out of 27 of reference periods at Fasa and Kerman stations, respectively. Therefore, it can be concluded that based on the CCF method, rapeseed and barley were the most sensitive and the most resistant species to drought at almost all stations, respectively, and winter wheat had moderate drought sensitivity compared to barley and rapeseed. Some factors such as shorter growth period in barley than winter wheat and rapeseed, less evapotranspiration in barley than winter wheat and rapeseed, etc. play an effective role on the results of the study. Katerji et al. (2009) assessed the sensitivity of wheat and barley to drought. The results of this research indicated that the sensitivity of wheat to drought is more than barley. It seems that the results of this paper are comparable to our results.

4 Conclusions

Given the importance of sustainable food security in the world and the central role of wheat, barley, and rapeseed in this field, recognizing the effective parameters on the yield of the above-mentioned species can help to reduce the risk of food security. Drought occurrence is one of the effective parameters on the yield of the mentioned species. Therefore, in the present study, we tried to assess the susceptibility of winter wheat, barley and rapeseed to drought using GEE and CCF models. The results of this study indicated that based on the GEE model used at all stations, rapeseed was the most sensitive species to drought

Table 10 *CC* coefficients between simulated and predicted annual yield of rapeseed using AquaCrop model and GEE method

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.680	0.754	0.692	0.901	0.757	0.508	0.748	0.732	0.876	0.799
	Nov	0.677	0.722	0.682	0.849	0.737	0.491	0.657	0.722	0.878	0.766
	Dec	0.694	0.657	0.673	0.850	0.745	0.486	0.665	0.731	0.875	0.770
	Jan	0.682	0.724	0.711	0.896	0.739	0.513	0.683	0.730	0.891	0.782
	Feb	0.678	0.766	0.703	0.900	0.740	0.635	0.774	0.731	0.933	0.785
	Mar	0.691	0.740	0.756	0.898	0.759	0.546	0.782	0.731	0.888	0.848
	Apr	0.802	0.693	0.681	0.854	0.864	0.497	0.692	0.882	0.880	0.783
	May	0.744	0.746	0.673	0.880	0.756	0.487	0.730	0.804	0.875	0.796
	Jun	0.723	0.791	0.680	0.891	0.753	0.503	0.720	0.777	0.882	0.786
	Jul	0.739	0.800	0.701	0.881	0.747	0.489	0.747	0.765	0.877	0.790
	Aug	0.717	0.823	0.685	0.886	0.762	0.520	0.712	0.766	0.886	0.801
3 months	Oct - Dec	0.687	0.708	0.683	0.858	0.739	0.492	0.705	0.734	0.875	0.767
	Nov - Jan	0.676	0.712	0.692	0.876	0.736	0.498	0.677	0.734	0.878	0.765
	Dec- Feb	0.676	0.757	0.706	0.914	0.738	0.609	0.765	0.730	0.915	0.783
	Jan - Mar	0.691	0.837	0.791	0.954	0.759	0.675	0.839	0.731	0.940	0.857
	Feb- Apr	0.761	0.792	0.757	0.910	0.835	0.595	0.827	0.790	0.921	0.848
	Mar- May	0.798	0.769	0.711	0.897	0.846	0.490	0.778	0.844	0.885	0.835
	Apr- Jun	0.812	0.767	0.683	0.885	0.825	0.485	0.729	0.869	0.879	0.800
	May–July	0.764	0.808	0.694	0.895	0.762	0.496	0.751	0.798	0.877	0.812
	Jun- Aug	0.737	0.822	0.702	0.892	0.761	0.521	0.735	0.774	0.885	0.804

Table 10 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.677	0.825	0.780	0.931	0.761	0.612	0.833	0.734	0.912	0.827
	Nov- Apr	0.728	0.793	0.762	0.923	0.811	0.576	0.819	0.770	0.915	0.841
	Dec- May	0.753	0.799	0.731	0.928	0.815	0.550	0.811	0.788	0.920	0.846
	Jan- Jun	0.780	0.849	0.742	0.953	0.824	0.566	0.803	0.814	0.937	0.856
	Feb- July	0.789	0.850	0.738	0.923	0.821	0.560	0.802	0.825	0.912	0.849
	Mar- Aug	0.809	0.837	0.733	0.908	0.823	0.514	0.768	0.837	0.892	0.849
12 months	Oct- Sep	0.756	0.852	0.751	0.932	0.811	0.557	0.776	0.800	0.907	0.843

Note. *CC* coefficients in all station and all-time scales were significant at 0.01 level

Table 11 |*Cross Correlations*| between simulated annual yield of winter wheat using AquaCrop model and SPEI

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.054	0.437	0.175	0.569	0.195	0.197	0.448	0.089	0.074	0.305
	Nov	0.103	0.317	0.071	0.169	0.068	0.137	0.176	0.236	0.064	0.055
	Dec	0.165	0.055	0.104	0.089	0.179	0.084	0.006	0.102	0.058	0.117
	Jan	0.062	0.256	0.022	0.430	0.009	0.057	0.125	0.019	0.171	0.089
	Feb	0.006	0.561	0.002	0.687	0.066	0.439	0.401	0.115	0.600	0.013
	Mar	0.146	0.557	0.517	0.693	0.218	0.268	0.617	0.050	0.483	0.514
	Apr	0.538	0.375	0.176	0.172	0.633	0.079	0.329	0.603	0.196	0.317
	May	0.422	0.417	0.095	0.473	0.161	0.036	0.374	0.398	0.071	0.247
	Jun	0.301	0.580	0.121	0.489	0.149	0.232	0.406	0.363	0.111	0.159
	Jul	0.347	0.529	0.290	0.478	0.111	0.356	0.413	0.337	0.012	0.222
	Aug	0.326	0.584	0.211	0.541	0.221	0.336	0.317	0.351	0.280	0.217
3 months	Oct - Dec	0.078	0.314	0.043	0.270	0.063	0.158	0.317	0.133	0.009	0.147
	Nov - Jan	0.029	0.275	0.023	0.387	0.033	0.120	0.137	0.127	0.142	0.037
	Dec- Feb	0.021	0.468	0.056	0.626	0.011	0.382	0.292	0.027	0.392	0.013
	Jan - Mar	0.121	0.713	0.332	0.903	0.170	0.457	0.602	0.079	0.672	0.380
	Feb- Apr	0.393	0.685	0.381	0.787	0.514	0.375	0.638	0.397	0.673	0.458
	Mar- May	0.524	0.598	0.375	0.643	0.526	0.116	0.561	0.516	0.410	0.486
	Apr- Jun	0.567	0.540	0.170	0.468	0.464	0.076	0.418	0.572	0.175	0.324
	May–July	0.455	0.575	0.230	0.522	0.174	0.226	0.445	0.407	0.094	0.289
	Jun- Aug	0.366	0.608	0.255	0.526	0.190	0.327	0.406	0.368	0.158	0.243

Table 11 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.051	0.655	0.283	0.771	0.187	0.415	0.594	0.130	0.524	0.365
	Nov- Apr	0.321	0.626	0.279	0.739	0.414	0.338	0.580	0.332	0.543	0.448
	Dec- May	0.397	0.638	0.248	0.736	0.400	0.300	0.540	0.382	0.535	0.414
	Jan- Jun	0.454	0.736	0.296	0.887	0.426	0.337	0.560	0.475	0.656	0.429
	Feb- July	0.479	0.739	0.357	0.813	0.426	0.382	0.573	0.498	0.567	0.433
	Mar- Aug	0.542	0.683	0.419	0.681	0.438	0.286	0.513	0.519	0.402	0.487
12 months	Oct- Sep	0.421	0.683	0.347	0.772	0.383	0.379	0.491	0.443	0.461	0.435

Table 12 |*Cross Correlations*| between simulated annual yield of barley using AquaCrop model and SPEI

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.242	0.104	0.031	0.118	0.062	0.018	0.138	0.076	0.029	0.038
	Nov	0.084	0.142	0.168	0.032	0.109	0.140	0.135	0.121	0.039	0.110
	Dec	0.233	0.019	0.040	0.098	0.072	0.163	0.155	0.009	0.202	0.067
	Jan	0.327	0.170	0.270	0.389	0.337	0.328	0.088	0.124	0.223	0.021
	Feb	0.338	0.017	0.239	0.093	0.331	0.171	0.208	0.316	0.058	0.329
	Mar	0.218	0.022	0.045	0.093	0.299	0.139	0.174	0.449	0.065	0.097
	Apr	0.367	0.063	0.070	0.043	0.092	0.125	0.080	0.037	0.160	0.159
	May	0.089	0.018	0.137	0.192	0.022	0.130	0.118	0.059	0.094	0.011
	Jun	0.025	0.019	0.083	0.145	0.238	0.122	0.161	0.031	0.022	0.229
	Jul	0.030	0.141	0.133	0.181	0.194	0.162	0.117	0.116	0.015	0.145
	Aug	0.046	0.059	0.056	0.220	0.184	0.031	0.106	0.197	0.059	0.003
3 months	Oct - Dec	0.048	0.076	0.084	0.105	0.132	0.045	0.206	0.136	0.164	0.163
	Nov - Jan	0.111	0.121	0.082	0.276	0.093	0.215	0.094	0.039	0.245	0.130
	Dec- Feb	0.254	0.063	0.256	0.325	0.369	0.328	0.172	0.221	0.346	0.169
	Jan - Mar	0.383	0.095	0.213	0.287	0.460	0.291	0.166	0.393	0.230	0.096
	Feb- Apr	0.467	0.004	0.088	0.115	0.347	0.121	0.140	0.367	0.032	0.011
	Mar- May	0.323	0.008	0.040	0.150	0.201	0.103	0.107	0.206	0.127	0.125
	Apr- Jun	0.255	0.030	0.003	0.175	0.133	0.006	0.100	0.014	0.114	0.025
	May–July	0.039	0.071	0.034	0.190	0.173	0.016	0.149	0.059	0.044	0.147
	Jun- Aug	0.023	0.085	0.103	0.182	0.254	0.103	0.136	0.114	0.001	0.152

Table 12 (continued)

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.338	0.119	0.149	0.286	0.269	0.220	0.246	0.184	0.284	0.046
	Nov- Apr	0.426	0.059	0.115	0.288	0.343	0.203	0.181	0.218	0.240	0.072
	Dec- May	0.364	0.036	0.182	0.300	0.332	0.233	0.151	0.249	0.219	0.007
	Jan- Jun	0.392	0.046	0.137	0.308	0.361	0.174	0.162	0.231	0.097	0.041
	Feb- July	0.322	0.052	0.035	0.197	0.309	0.042	0.180	0.200	0.076	0.059
	Mar- Aug	0.234	0.052	0.053	0.208	0.267	0.018	0.513	0.107	0.098	0.045
12 months	Oct- Sep	0.287	0.072	0.013	0.292	0.280	0.066	0.181	0.050	0.169	0.042

Table 13 |*Cross Correlations*| between simulated annual yield of rapeseed using AquaCrop model and SPEI

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
1 month	Oct	0.099	0.492	0.221	0.573	0.264	0.170	0.478	0.084	0.079	0.357
	Nov	0.036	0.397	0.152	0.044	0.055	0.082	0.071	0.217	0.154	0.071
	Dec	0.213	0.022	0.010	0.089	0.171	0.017	0.158	0.076	0.025	0.141
	Jan	0.121	0.405	0.310	0.543	0.107	0.189	0.258	0.001	0.347	0.253
	Feb	0.065	0.522	0.277	0.567	0.119	0.468	0.546	0.074	0.667	0.276
	Mar	0.191	0.453	0.467	0.555	0.275	0.287	0.567	0.065	0.318	0.570
	Apr	0.584	0.294	0.141	0.175	0.668	0.122	0.299	0.726	0.205	0.261
	May	0.421	0.470	0.000	0.483	0.255	0.037	0.429	0.493	0.004	0.343
	Jun	0.345	0.584	0.217	0.511	0.234	0.156	0.396	0.392	0.234	0.283
	Jul	0.405	0.608	0.268	0.446	0.188	0.227	0.477	0.334	0.137	0.305
	Aug	0.323	0.657	0.175	0.483	0.294	0.235	0.370	0.340	0.347	0.368
3 months	Oct - Dec	0.164	0.349	0.164	0.233	0.099	0.089	0.348	0.123	0.062	0.084
	Nov - Jan	0.003	0.363	0.217	0.410	0.026	0.126	0.230	0.119	0.166	0.046
	Dec- Feb	0.008	0.498	0.291	0.640	0.085	0.421	0.523	0.016	0.552	0.263
	Jan - Mar	0.195	0.689	0.563	0.824	0.273	0.536	0.694	0.068	0.713	0.599
	Feb- Apr	0.475	0.586	0.470	0.622	0.583	0.393	0.669	0.444	0.595	0.569
	Mar- May	0.575	0.529	0.313	0.550	0.617	0.077	0.556	0.621	0.280	0.519
	Apr- Jun	0.610	0.524	0.158	0.474	0.550	0.007	0.426	0.690	0.174	0.365
	May–July	0.482	0.625	0.230	0.535	0.290	0.117	0.487	0.473	0.125	0.422
	Jun- Aug	0.399	0.655	0.270	0.521	0.286	0.216	0.444	0.377	0.280	0.384

Table 13 |*Cross Correlations*| between simulated annual yield of rapeseed using AquaCrop model and SPEI

Reference period		Arak	Birjand	Esfahan	Fasa	Ghazvin	Kerman	Sabzevar	Sanandaj	Shiraz	Teh-ran
6 months	Oct- Mar	0.054	0.662	0.533	0.722	0.286	0.427	0.682	0.115	0.530	0.489
	Nov- Apr	0.364	0.590	0.483	0.688	0.505	0.354	0.651	0.362	0.556	0.541
	Dec- May	0.448	0.603	0.385	0.709	0.518	0.296	0.633	0.435	0.585	0.561
	Jan- Jun	0.528	0.714	0.423	0.818	0.549	0.333	0.616	0.528	0.692	0.595
	Feb- July	0.553	0.716	0.409	0.684	0.539	0.320	0.613	0.565	0.535	0.573
	Mar- Aug	0.602	0.687	0.394	0.612	0.544	0.193	0.531	0.599	0.364	0.573
12 months	Oct- Sep	0.459	0.719	0.451	0.730	0.503	0.312	0.552	0.481	0.498	0.552

and barley was the most resistant species to drought. The CCF analysis to susceptibility assessment of mentioned species to drought showed that rapeseed and barley were the most sensitive and the most resistant species to drought at Arak, Birjand, Esfahan, Ghazvin, Sabzevar, Sanandaj, Shiraz and Tehran stations, respectively, while winter wheat and barley were the most sensitive and the most resistant species to drought at Fasa and Kerman stations. Finally, based on the results, it is suggested that barley can be the first choice of cultivation, wheat can be the second and rapeseed can be the third for farmers in order to reduce the negative effects of drought on the annual yield of the mentioned species, and reduce economic losses, especially in the central and southern parts of Iran where the occurrence of drought is more frequent.

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Data Availability The data used in this research are available by the corresponding author upon reasonable request.

Declarations

Ethics Approval The authors confirm that this article is original research and has not been published or presented previously in any journal or conference in any language (in whole or in part).

Consent to Participate and Consent to Publish not applicable.

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