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Determining optimum planting dates for rainfed wheat using the precipitation uncertainty model and adjusted crop evapotranspiration

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ABSTRACT

Weather variables such as maximum and minimum temperatures and precipitation influence crop production especially under rainfed conditions. The goal of this study was to determine the optimum planting date of rainfed wheat based on crop evapotranspiration under water stress conditions ($ET_{c\,adj}$), using modeled precipitation uncertainty. This analysis was conducted for 5 locations in the Khorasan province (Mashhad, Sabzevar, Birjand, Bojnourd and Torbat-heydarye) in Iran, using five planting dates at 15 day interval (23 Sep to 23 Nov). The climate data for each location ranged from 29 years to 44 years containing daily values of maximum temperature, minimum temperature, and precipitation. Evapotranspiration was calculated using the FAO (Food and Agricultural Organization of the United Nations) modified form of the Penman–Monteith equation (FAO 56). Cumulative values of $ET_{c\,adj}$ for all locations except Sabzevar showed the highest values for the final planting date with a sharp increase at the end of the growth period. However, there was no difference among the different planting dates of rainfed wheat for Sabzevar. Rainfed wheat experienced extreme and medium drought conditions based on the calculated Dry Days Since Last Rain (DDSLR) index which represents the number of drought days (DDN) during the growing season. Rainfed wheat planted at the final planting date was exposed to the lowest drought intensity during the growth period for all study locations. Planting a rainfed crop based on the occurrence of the first precipitation is not always a suitable strategy for drought avoidance. The approach introduced here will improve the appropriate selection of representative planting dates that will produce highest potential yield under rainfed conditions.

1. Introduction

Crop yield is affected by the variation in weather variables such as air temperature, precipitation, and frequency and severity of extreme events such as drought (Alexandrov and Hoogenboom, 2000; Bannayan and Sanjani, 2011). Water stress is considered to be the most important limiting factor for crop growth and production in arid and semiarid regions (Dogan et al., 2007). Wheat is one of the most widely grown crops around the world and approximately one-sixth of the total arable land in the world is currently under wheat cultivation (Zwart et al., 2010). Approximately 90% area of Iran is considered as arid and semiarid and wheat is the dominant crop of the local cropping systems (Bannayan et al., 2010). According to the FAO Statistics (2008), 4.7 billion hectare land with an average grain yield of 4.2 $t\,ha^{-1}$ (irrigated) and 1.1 $t\,ha^{-1}$ (rainfed) is under wheat cultivation in Iran. The province of Khorasan in the northeast of Iran contains the largest area of cultivated fields (72,000 ha), and its average rainfed wheat yield is around 1 $t\,ha^{-1}$ (Khorasan Jehad-Agriculture Organization Statistics, 2008). Precipitation is a critical factor for various geomorphological, hydrological, ecological and agricultural processes, especially in arid and semi arid regions (Sepaskhah et al., 2006). Crop production in dryland regions is mainly determined by precipitation and is extremely vulnerable to changes in precipitation patterns and amounts. This vulnerability increases as total precipitation decreases and/or the number of dry days increases. A dry day is defined as a day with no measurable precipitation or a day when the total measured precipitation is below a determined daily precipitation threshold (DRT). The Dry Days Since Last Rain (DDSLR) index was introduced by Reiser and Kutiel (2010) to highlight problems which often occur in using various methods for evaluation of drought intensity (Reiser and Kutiel, 2010). This index defines the number of dry days during the growing season by counting days when the precipitation amount is less than DRT.

Evapotranspiration is one of the major components of the hydrologic cycle and its accurate estimation is of paramount importance for many studies such as the hydrological water balance,

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irrigation system design and management, crop yield simulation, and water resources planning and management (Garcia et al., 2003). Using crop coefficients for the calculation of crop evapotranspiration (ETc) was first introduced by Doorenbos and Pruitt (1977), whereby the effect of the climate on crop water requirements is given by the reference evapotranspiration (ET_o) and the effect of the specific crop characteristics by the crop coefficient (K_c). The K_c is the ratio of the crop ET to the reference ET and represents the integrated effects of a series of characteristics that distinguishes the crop from reference grass. These characteristics include crop height, canopy resistance, soil evaporation, and the albedo of the crop–soil surface (Miranda et al., 2006). The FAO 56 model, which incorporates thermodynamic and aerodynamic aspects, has proven to be a relatively accurate method for both humid and arid climates (Yin et al., 2008). Crop evapotranspiration has a significant correlation with crop production (Harmsen et al., 2009).

The appropriate selection of a planting date can have a dramatic impact on both the quantity and quality of crop yield (Gul et al., 2008). Changing the planting date can expose a crop to adverse environmental conditions. Planting date affects the grain protein percentage mainly through the pattern of the thermal conditions prevailing during the grain filling period. Late sown material generally flowers late, thereby forcing the grain filling period to coincide with a high temperature regime. Extreme temperature and drought during grain filling have been identified as major source of variation of wheat flour quality characteristics (Singh et al., 2010). Nakano and Morita (2009) reported that early planting could significantly increase dry matter accumulation of forage rice, and found that early planting improved forage yield by increasing the number of tillers in comparison with the normal planting time. Considering the limitations of soil moisture, planting too early to take advantage of the fall precipitation can cause excessive growth which usually results in low available soil moisture for early spring growth (Winter and Musick, 1993). The objective of this study was to determine the optimum planting date of rainfed wheat in the Khorasan province based on crop evapotranspiration under soil water stress conditions ($ET_{c\ adj}$) and outputs of a precipitation uncertainty model.

2. Materials and methods

2.1. Study area and data sets

The Khorasan province covers an area of about 248,000 square kilometers in the northeastern Iran (Fig. 1). This extensive area is inhabited by more than 6 million people and agriculture plays a vital economic role. The climate of the Khorasan province is very variable (Bannayan et al., 2010). However, rainfed farming of wheat is the dominant cultivation pattern due to the semiarid conditions. Mashhad, Birjand, Bojnourd, Torbat-heydariye and Sabzevar are dominant agricultural regions in Khorasan. These regions are located between the latitude of 32° and 37° N. The climatic characteristics of the study region are presented in Table 1. The weather data sets for each location ranged from 29 years to 44 years containing daily values of maximum temperature (T_{max}), minimum temperature (T_{min}), and precipitation. Average precipitation across the Khorasan province during the last 40 years was 222 mm and varied from 169 mm at the southern area (Birjand) to 269 mm in northern area (Bojnourd). Generally, precipitation is rare from July to September for all locations. The lowest values of T_{max} and T_{min} were obtained in Bojnourd (19.6 °C and 6.7 °C), while Birjand and Sabzevar had the highest T_{max} (24.4 °C) and T_{min} (10.7 °C) respectively (IMO, 2010).

The planting dates of rainfed wheat for the study locations range from 23 Sep to 21 Nov based on occurrence of the first effective

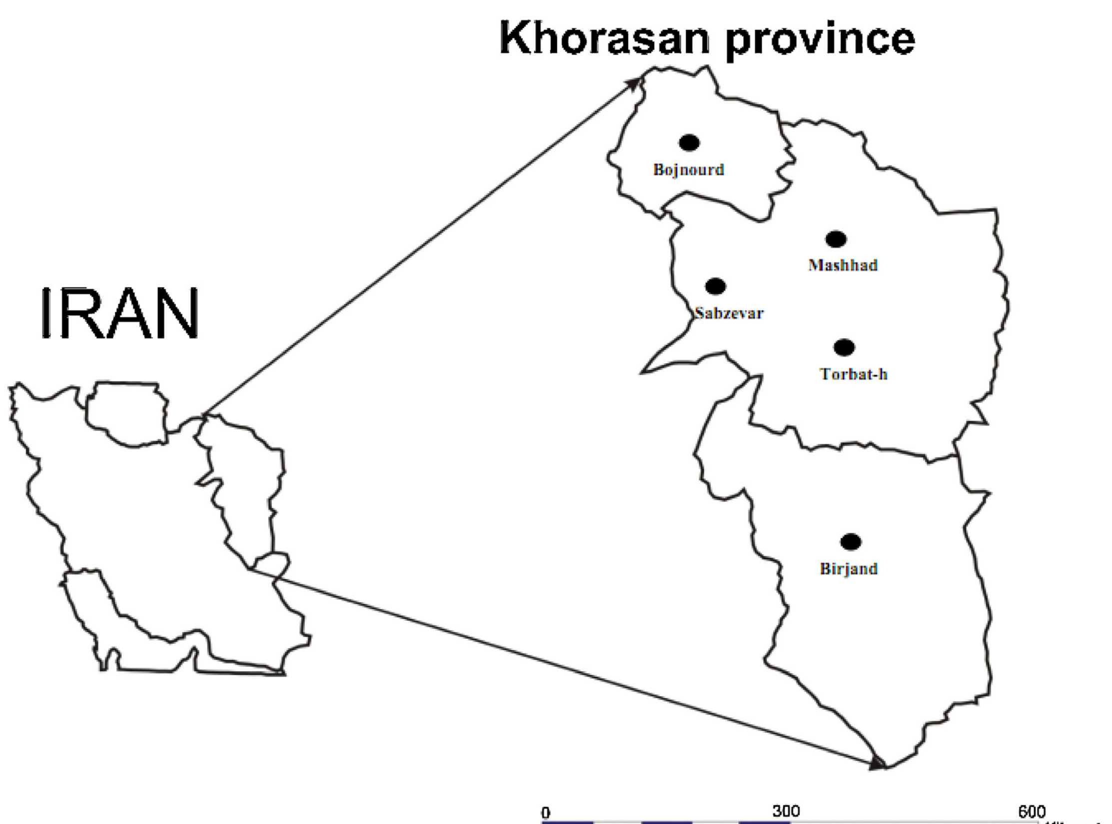

Fig. 1. Study locations in Iran.

Table 1
Climatological characteristics for the locations in this study.

Location	Longitude	Latitude	Elevation (m)	T_{max} (°C)	T_{min} (°C)	Daily rainfall threshold (mm)	Number of study years	Total annual rainfall (mm)
Birjand	59°12′ E	32°52′ N	1491	24	8	1.2	29	169
Bojnourd	57°19′ E	37°28′ N	1091	20	7	1	35	273
Mashhad	59°38′ E	36°16′ N	999	21	7	1.2	40	256
Sabzevar	57°43′ E	36°12′ N	977	24	11	1.2	40	192
Torbat-heydariye	59°13′ E	35°16′ N	1450	19	7	1.5	35	274

T_{max}: annually average of maximum temperature; T_{min}: annually average of minimum temperature

rain. This period can accommodate 5 planting dates with a 15-day interval based on calculated daily Dry Days Since Last Rain (DDSLR) and Adjusted Crop Evapotranspiration ($ET_{c\ adj}$) for 180 continuous days.

2.2. Calculation of Dry Days Since Last Rain (DDSLR)

The analysis was performed according to the Precipitation Uncertainty Evaluation Model (RUEM 5) developed by Reiser and Kutiel (2008). Analysis of DDSLR requires precipitation starting analysis date (SAD) and the calculation of the daily precipitation threshold (DRT). Starting analysis date (SAD) determines the date on which the analyses starts in each location as defined by Reiser and Kutiel (2008). Study locations represented a uni-model annual course of precipitation with a shorter rainy season length during the summer. The minimum precipitation requirement for the beginning of any process which requires water from precipitation can be defined as the required precipitation threshold. Traditionally 1.0 mm is used for most regions as a measurable quantity of rain (Romero et al., 1998). The determination of accurate values for DRT may significantly impact drought occurrence and intensity for semi-arid regions. Instead of setting one fixed threshold for all study locations, a certain percentile of the total annual precipitation of the selected location will better represent and characterize the precipitation regime. A one millimeter threshold for a location means a different percentage of the annual precipitation in another, given that each location has its own precipitation regime. The DRT in each location was determined as the rainy days that contribute to 5% of the total annual precipitation. This was performed in order to remove very low amounts of precipitation which mask the core precipitation regime and may present an obstacle in trying to evaluate correctly any significant change in the precipitation regime (Reiser and Kutiel, 2009).

DDSLR was calculated by counting the number of rainy and dry days and the difference between them (Aviad et al., 2004). Each rainy day when at least the DRT was recorded means that this day was not added to the number of dry days since the last rain. The dry day number (DDN) is set to “1” the first day after a rainy day in which there was no measurable rain that was equal or above the DRT. The next consecutive dry day becomes “2” and so on until the next occurrence of a rainy day, which resets the dry day number to “0” (Reiser and Kutiel, 2010). The DDSLR was accumulated from one year to the next year for the different planting dates regardless of the SAD.

Two threshold as DDSLR (50%) and DDSLR (90%) were determined to illustrate medium and extreme dryness conditions for each location. The importance of DDSLR (50%) for a certain day is that, for half of the years that were analyzed, the DDSLR was shorter than this threshold and for half the years it was longer. Similarly, DDSLR (90%) means that, in 90% of the years, the DDSLR was shorter than this threshold, whereas in 10% of the years, the DDSLR was longer (Reiser and Kutiel, 2010).

2.3. Crop evapotranspiration under soil water stress conditions ($ET_{c\ adj}$)

The $ET_{c\ adj}$ (mm d^{-1}) was estimated as (Allen et al., 1998):

$$ET_{c\ adj} = K_s \times K_c \times ET_0 \quad (1)$$

2.3.1. Water stress coefficient (K_s)

The effects of soil water stress on crop ET were imposed by reducing the value of the crop coefficient (K_s). The crop stress coefficient, K_s, was determined as:

$$K_{s,i} = \frac{TAW_i - D_{r,i}}{TAW_i - RAW_i} \quad (2)$$

where $K_{s,i} = 1$ when $D_{r,i}$ (root zone depletion [mm]) is smaller than or equal to Readily Available Water (RAW_i), otherwise $K_s < 1$. For a given day, total available water (TAW_i) is determined from the daily crop rooting depth ($Z_{r,i}$), Field Capacity (FC) and Permanent Wilting Point (PWP) for a soil at the rooting depth. The RAW_i is then expressed as $pTAW_i$, where p is the soil depletion factor that represents the fraction of TAW_i that can be depleted from the root zone before water-stress occurs.

2.3.2. Crop coefficient (K_c)

Crop development takes place in four stages, initial, crop development, mid season and late season. The length of each stage was determined from local information and the length of growing season was based on farmers' practices in the study area (Gontia and Tiwari, 2009). Monthly crop coefficient (K_c) was estimated using the guidelines given in the Irrigation and Drainage Manual FAO-56 (Allen et al., 1998) for wheat depending upon the stage of growth and adjusted by following equations:

$$K_{cmid} = K_{cmid(tab)} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)] \left(\frac{h}{3}\right) \times 0.3 \quad (3)$$

$$K_{cend} = K_{cend(tab)} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)] \left(\frac{h}{3}\right) \times 0.3 \quad (4)$$

where $K_{c\ mid(tab)}$ and $K_{c\ end(tab)}$ are the tabulated values for $K_{c\ mid}$ and $K_{c\ end}$ respectively in Table 12 of FAO 56 (Allen et al., 1998). $RH_{\min}$ is the mean value for daily minimum relative humidity during the midseason growth stage (%), for $20\% \le RH_{\min} \le 80\%$, u_2 is wind speed measured at 2 m above the ground, and h is mean plant height during the mid-season stage (m) for $0.1\ \text{m} < h < 10\ \text{m}$ (Gontia and Tiwari, 2009).

2.3.3. Reference evapotranspiration (ET_0)

Potential evapotranspiration for each day was calculated using the FAO (Food and Agricultural Organization of the United Nations) modified form of the Penman–Monteith equation (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\left(\frac{900}{T+273}\right) \times u_2 \times (e_s - e_a)}{\Delta + \gamma(1 + 0.34 \times u_2)} \quad (5)$$

where ET_0 is the reference evapotranspiration (mm d^{-1}), Δ is the slope of the vapor pressure curve, R_n is the net radiation at the surface (MJ m^{-2} d^{-1}), G is the soil heat flux density (MJ m^{-2} d^{-1}), g is the psychrometric constant, T is the mean daily air temperature at 2 m height, u_2 is the wind speed at 2 m height, e_s is the saturated vapor pressure and e_a is the actual vapor pressure (kPa). Daily values of total solar radiation at the earth's surface (R_s) were estimated using the procedure of Hargreaves and Samani (1982) and as subsequently modified by Allen (1997). Extraterrestrial solar radiation (R_a) (MJ m^{-2} d^{-1}) was first calculated at the top of the earth's atmosphere for each study day based on latitude, longitude, and the solar constant (Allen, 1997). Then, R_s was calculated using the following equation:

$$R_s = K_{Rs}(1 + 2.7 \times 10^{-15} \times Alt) \times (T_{\max} - T_{\min})0.5 \times R_a \quad (6)$$

where Alt is the altitude (m) and K_{Rs} is an empirical coefficient set at 0.16 (Hargreaves and Samani, 1982). Clear-sky solar radiation (R_{so}) was calculated by the following equation (Allen et al., 1998):

$$R_{so} = (0.75 + 2 \times 10^{-5}z)R_a \quad (7)$$

where z is the station elevation above sea level (m). In addition, net shortwave radiation (R_{ns}) was obtained using the following formula (Allen et al., 1998):

$$R_{ns} = (1 - \alpha)R_s \quad (8)$$

In which, α is the albedo or canopy reflection coefficient, which is 0.23 for the hypothetical grass reference crop. Net longwave radiation (R_{nl}), which is the rate of longwave energy emission, is proportional to the absolute temperature of the surface raised to the fourth power, calculated as follows (Allen et al., 1998):

$$R_{nl} = \sigma\left[\frac{T_{\max,k^4} + T_{\min,k^4}}{2}\right] \times (0.34 - 0.14\sqrt{e_a}) \times \left(1.35\frac{R_s}{R_{so}} - 0.35\right) \quad (9)$$

where σ is Stefan–Boltzmann constant (4.903×10^{-9} MJ K^{-4} m^{-2} d^{-1}) and finally, net radiation at the surface (R_n) obtained by differences between R_{ns} and R_{nl}.

2.3.3.1. Vapor pressure deficit ($e_s - e_a$). The calculation of VPD was based on the difference between the average daily saturated water vapor pressure and the actual water vapor pressure. An estimation of actual vapor pressure can be obtained by assuming that dew point temperature (T_{dew}) is near the daily minimum temperature that for most conditions occurs around sunrise. In addition, saturated water vapor pressure was calculated by averaging of saturation vapor pressure at the minimum and maximum temperature (e^0) using the following equation (Allen et al., 1998):

$$VPD = \left(0.611 \exp\left[\frac{17.27T_{dew}}{T_{dew} + 237.3}\right]\right) - \left(\frac{e^0(T_{\max}) + e^0(T_{\min})}{2}\right) \quad (10)$$

2.4. Statistical analysis

Basic statistics of annual average temperature and precipitation sum including mean, median and standard deviation were calculated and Anderson–Darling test along with probability plot were used for testing the normality of climate data. The Anderson–Darling test was conducted using the following equation (Stephens, 1974):

$$AD = -n - \frac{1}{n}\sum_{i=1}^{n}(2i - 1)[\ln F(X_i) + \ln(1 - F(X_{n-i+1}))] \quad (11)$$

where n and $F(X)$ are number of years and cumulative distribution function for the normal distribution, respectively and i is the ith year when the data is sorted in ascending order. Finally, the cumulative values of adjusted crop evapotranspiration during growing season of the different planting dates were calculated for all years and study locations. Furthermore, descriptive statistics such as mean, median and standard deviation of cumulative values were calculated to show the variability of adjusted crop evapotranspiration values.

2.5. Determination of optimum planting date

At the final step, optimum planting date was determined based on cumulative values of adjusted ET_c and DDN during the growing season of rainfed wheat across the study locations. The selected optimum planting date indicated the highest cumulative values of adjusted ET_c and lowest number of DDN for each location. In addition, the variability of adjusted ET_c across study years considered for increasing the accuracy and confidence of the optimum planting date determinations.

3. Results

3.1. Climatic variables

Annual mean temperature standard deviation was less than 1.50 °C (0.66–1.24 °C) for all study locations (Fig. 2). In addition, testing the normality showed that Anderson–Darling test was not significant and, therefore, study climate variables followed the normal probability (Fig. 2).

The variability of total precipitation was higher than the variability of the annual mean temperature across study locations. The standard deviation ranged from 50 mm to 76 mm for the Birjand and Torbat-heydariye locations, respectively (Fig. 2). Furthermore, the differences between mean and median were higher in Torbat-heydariye, Mashhad and Bojnourd as these locations had the highest standard deviation values. The values for total precipitation during the study period followed the normal probability across all locations (Fig. 2).

3.2. Adjusted crop evapotranspiration ($ET_{c\ adj}$)

Accumulated values of $ET_{c\ adj}$ were used to determine the suitable planting date of the rainfed wheat for all study locations. In general, delaying the planting date gradually raised the cumulative values of $ET_{c\ adj}$. The mean values of accumulated $ET_{c\ adj}$ showed significant differences among the planting dates for all study locations. The first (23 Sep) and final (23 Nov) planting dates represented the lowest and highest mean values of $ET_{c\ adj}$ across study locations (Table 2).

One month delay in planting increased the accumulated $ET_{c\ adj}$ from 158 mm to 241 mm for Birjand, while this difference in accumulated $ET_{c\ adj}$ was 21 mm for Sabzevar (Table 2). The difference between the mean and median of the accumulated $ET_{c\ adj}$ ranged from 8 mm (Torbat-heydariye, final planting date) to −2 mm (Sabzevar, third planting date) (Table 2).

The highest values for standard deviation were obtained for the final planting date for all locations except Mashhad. The standard deviation ranged from 22.5 mm to 16.3 mm across locations and planting dates (Table 2). The lowest value for the standard deviation

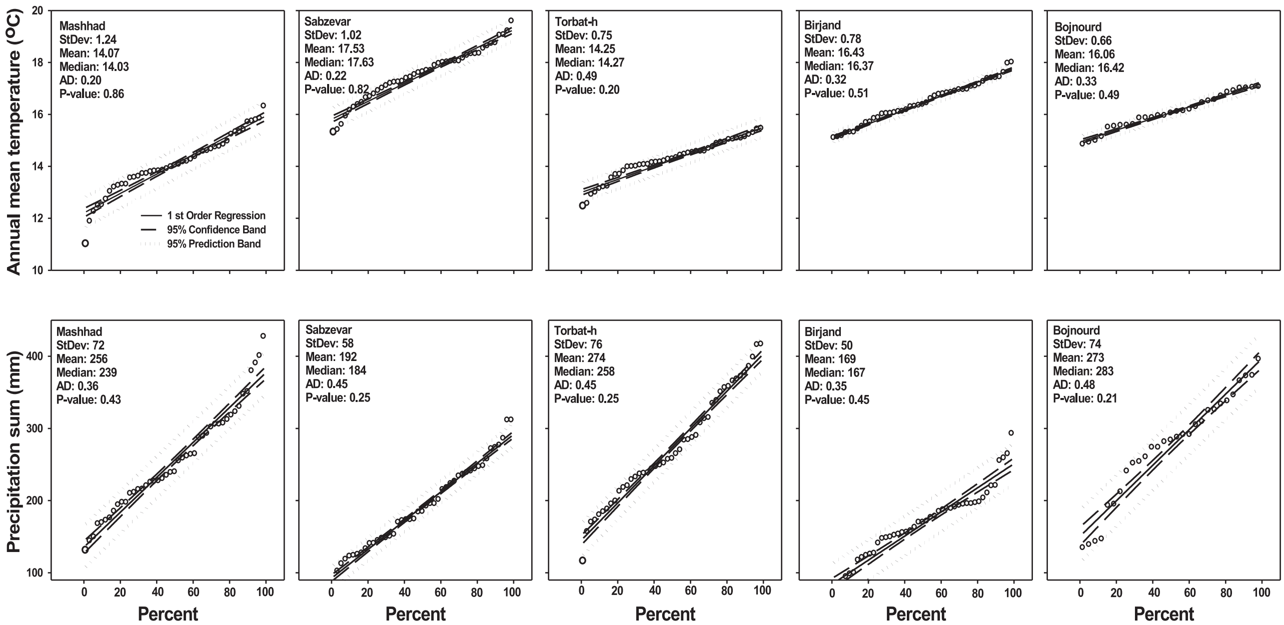

Fig. 2. Probability plot of annual mean temperature and precipitation sum and Anderson–Darling test for normal probability across study locations (StDev: standard deviation and AD: Anderson–Darling test value).

was found for Birjand (16.3 mm) and the highest one was found for Torbat-heydariye (22.5 mm) (Table 2).

3.3. *Dry Days Since Last Rain (DDSLR)*

3.3.1. *Mashhad*

Precipitation is the most important environmental factor that affects yield of rainfed crops in arid and semi arid regions across the world (Lopez-Castaneda and Richards, 1994). The DDN based on the first planting date showed significant differences in extreme DDSLR (90%) and medium DDSLR (50%) drought conditions until 60 days after planting. Then this difference decreased for the remainder of the growing season (Fig. 3). The DDN for the second (7 Oct) (Fig. 3), third (22 Oct) (Fig. 3) and fourth (6 Nov) planting dates (Fig. 3) had a similar trend as the first planting date. However, the DDN and the differences between extreme and medium drought conditions decreased for the later planting dates. Rainfed wheat planted on the final planting date (23 Nov) in Mashhad was exposed to the lowest DDN for the growing season for extreme and medium drought conditions (Fig. 3).

Table 2
Summary statistics of the cumulative values of adjusted total evapotranspiration during growing season for the different planting dates across study locations.

Location	Planting date	Mean	Median	StDev	Maximum	Minimum
Mashhad	23 Sep	163.9	160.9	34.7	228.0	105.0
	7 Oct	154.0	154.0	17.7	182.0	122.0
	22 Oct	158.6	157.0	15.5	189.0	123.0
	6 Nov	179.7	177.0	24.5	246.0	133.5
	23 Nov	213.0	215.0	24.1	255.0	159.7
Sabzevar	23 Sep	162.9	163.0	26.6	217.0	103.0
	7 Oct	165.5	166.0	17.9	197.0	126.0
	22 Oct	171.4	174.0	21.8	218.0	133.0
	6 Nov	177.4	174.0	22.9	241.0	137.0
	23 Nov	183.8	185.0	38.3	300.0	111.0
Birjand	23 Sep	158.4	161.0	14.5	117.8	124.7
	7 Oct	188.7	185.0	26.2	236.0	152.6
	22 Oct	195.1	186.9	29.7	261.0	153.0
	6 Nov	215.9	207.0	30.8	292.3	174.0
	23 Nov	241.5	236.8	30.5	309.7	176.1
Bojnourd	23 Sep	174.2	169.3	32.1	272.0	130.0
	7 Oct	165.8	164.0	20.2	233.0	133.0
	22 Oct	168.1	161.8	31.3	258.0	124.7
	6 Nov	185.1	180.2	35.3	283.0	141.5
	23 Nov	213.2	208.2	37.7	277.0	150.0
Torbat-heydariye	23 Sep	174.7	170.0	25.5	229.2	133.0
	7 Oct	163.8	157.8	19.1	207.0	132.0
	22 Oct	168.9	170.0	19.1	209.0	130.6
	6 Nov	190.9	188.0	31.5	255.0	137.2
	23 Nov	225.3	217.0	41.6	336.0	150.0

StDev: standard deviation.

3.3.2. *Birjand*

Birjand is one of the driest locations in the province of Khorasan. There was a dramatic difference between extreme and medium drought conditions (more than 100 dry days) for the first (Fig. 3) and second (Fig. 3) planting dates and rainfed wheat was exposed to drastic drought situations during the early and exponential growth stages in Birjand. A long dry-day period occurred during the early growth period of the final planting date in comparison to the later planting dates (Fig. 3). Drastic drought conditions for rainfed wheat only occurred during the first 20 days after planting for the final planting date and DDN was less than 15 days for the other growth stages under moderate drought conditions (Fig. 3).

3.3.3. *Bojnourd*

Bojnourd is situated in the northern part of province of Khorasan and it has the highest annual precipitation across the study regions. The first and second planting dates showed the highest DDN especially during the early growth period of rainfed wheat (Fig. 3). There was no significant difference between the third and fourth planting dates for DDN (Fig. 3). The final planting dates (23 Nov) had the smallest number of dry days and only a slight difference between extreme and medium drought conditions (Fig. 3). There was no significant difference in drought conditions between the final and fourth (Fig. 3) planting dates.

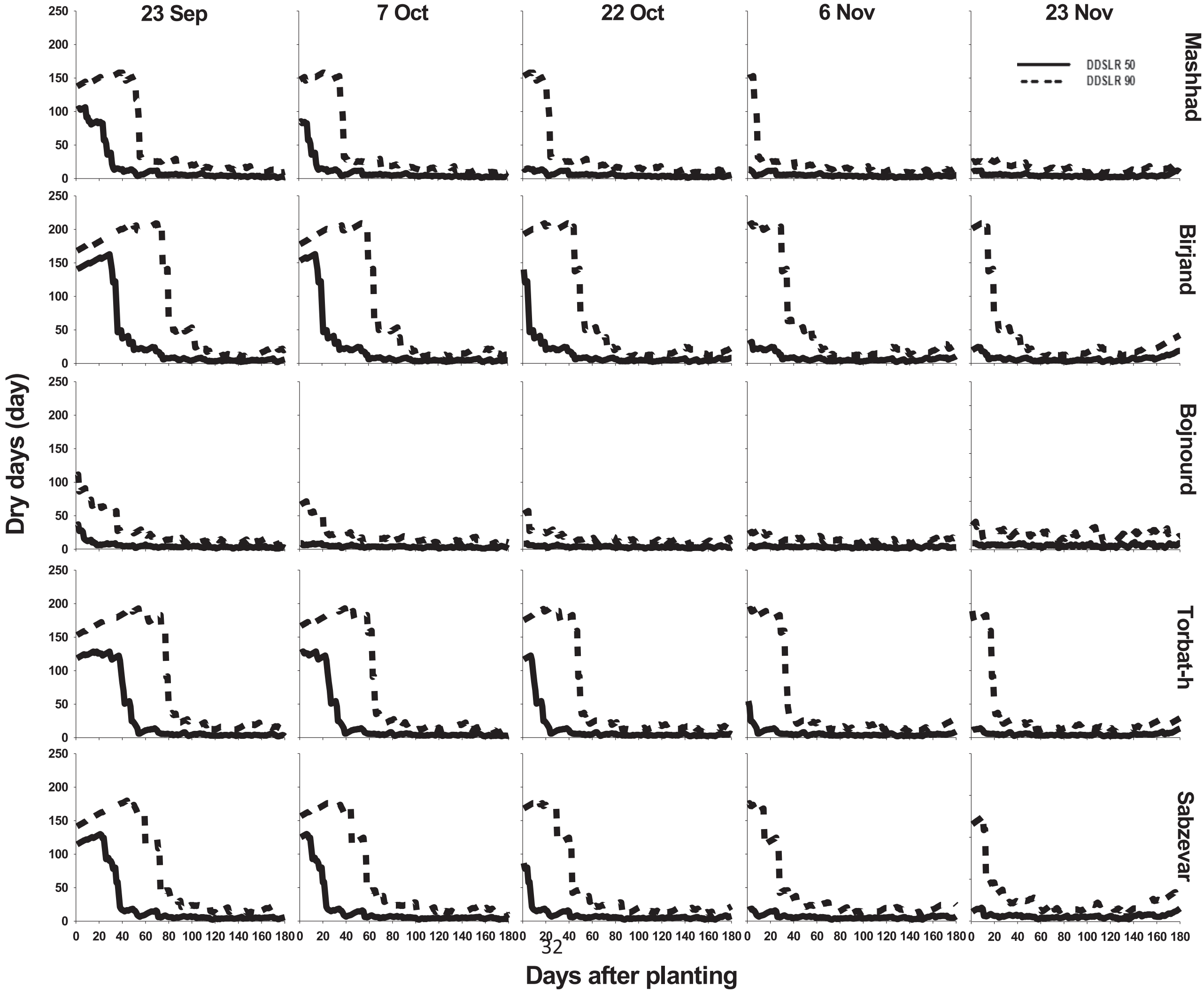

Fig. 3. Historical climate average values of Dry Days Since Last Rain (DDSLR) index (50%) (medium drought) and DDSLR (90%) (extreme drought) for all study locations for different planting dates.

3.3.4. Torbat-heydariye

The first (23 Sep) and second (7 Oct) planting dates had the highest DDN when compared to all planting dates and the largest differences between extreme and medium drought conditions (Fig. 3). For the third and fourth planting dates, early growth of rainfed wheat was exposed to drastic drought, e.g., more than 120 DDN (Fig. 3).

3.3.5. Sabzevar

Rainfed wheat planted on 23 Sep (Fig. 3) and 7 Oct (Fig. 3) was exposed to drastic drought (more than 120 DDN) until 60 days after planting. Furthermore, there was a sharp difference in DDN between extreme and medium drought conditions for these planting dates until 100 days after planting. The DDN dramatically decreased for the third (Fig. 3) and fourth (Fig. 3) planting dates. The final planting date indicated a high DDN just 10 days after planting and this planting date was more suitable than others in both extreme and medium drought conditions (Fig. 3).

4. Discussion

Crop production in arid and semi-arid regions can be seriously affected due to a lack of soil moisture during the growing season. It is imperative to improve the design of crop management systems in order to be able to make productive use of available soil moisture and to enhance crop productivity due to variable inter- and intra-seasonal precipitation and extreme weather factors. Based on the local average climatic conditions, the results of this study showed that the planting date had a direct impact on crop evapotranspiration, especially under limited soil moisture conditions, and determined the intensity of the drought. Soriano et al. (2004) showed that the planting date factor would be useful for delineating the optimum strategy for rainfed sunflower cropping systems. They showed that higher yield due to early planting was explained by an increase in transpiration and transpiration efficiency.

An optimum planting date can result in an earlier ground cover and thus reduce the relative importance of evaporation from the soil surface. For all study locations except Sabzevar, the cumulative values of $ET_{c\,adj}$ were higher for the final planting date (23 Nov) than for the other planting dates and the variability of $ET_{c\,adj}$ did not change the superiority of this final planting date. However, there was no difference among the final three planting dates when considering the variability of the standard deviation. The values for $ET_{c\,adj}$ were highly correlated to the differences between maximum and minimum temperature, with Sabzevar representing the smallest difference between maximum and minimum temperature. High values for evapotranspiration for the earlier planting dates resulted in high moisture loss due to evaporation which was thus not available for crop production.

Agele et al. (2011) concluded that the time course of soil water balance components especially crop consumptive water use shows a decrease in its values with an increase in ET_0 under rainfed situation. Soriano et al. (2004) used a crop model to determine the optimum planting date of rainfed sunflower in Spain based on water loss through evapotranspiration. Their study showed that there was a smaller water loss through the soil evaporation component of evapotranspiration due to a change in planting date, resulting in a higher yield for sunflower.

The Dry Days Since Last Rain (DDSLR) index analysis among the different planting dates showed that rainfed wheat for the final planting date was exposed to the smallest number of dry days especially for the dry locations in the southern and central parts of the Khorasan province. In addition, differences between extreme and medium drought conditions were smallest for the final planting date. For this planting date more precipitation occurred during the wheat growth period for all locations except Sabzevar, which showed no difference among the various planting dates. Water deficit during drought spells is one of the most significant stress factors on crop production worldwide (Narasimhan and Srinivasan, 2005; Bannayan and Hoogenboom, 2008). Sawa and Ibrahim (2011) showed that a 54.5% variation in millet yield was accounted for by occurrences of total dry spells during the growing season in their arid study area.

Based on the results of current study rainfed wheat experienced less drought stress and illustrated higher adjusted ET_c for later planting dates for northeast Iran. Applying late planting dates has both a number of advantages and disadvantages for rainfed wheat production. The most important advantage of late planting dates is avoiding drought stress during the early growth stages due to more water availability (Sharma and Acharya, 2000). On the other hand, the crop could be exposed to higher temperatures during the growing season and even extreme temperatures during sensitive growth stages such as anthesis due to a delay in planting date (Zhong-hu and Rajaram, 1994). In general, higher temperatures accelerate crop growth rate and decrease the growing season duration (Stone and Nicolas, 1994). Recent studies have shown that extreme temperatures (higher than 31 °C) occurred during anthesis significantly declined the grain number and final grain yield (Luo, 2011). The range of the mean temperature increase among the different planting dates varied from 1 °C to 3.5 °C across the study region. Therefore, it seems temperature increase due to late planting date may not significantly influence the growing length in study region. However, the frequency of extreme temperatures would increase by late planting of rainfed wheat across study locations. Thus, planning the mitigation strategies such as cultivation of heat resistance cultivars would be necessary.

In conclusion, a combination of the $ET_{c\ adj}$ and DDSLR index is a practical and applicable method for determining suitable planting dates of rainfed wheat or other rainfed crops for arid and semi-arid locations in comparison with indigenous knowledge which is based on the planting date according to beginning of the rainy season. However, decision makers should consider the side effects of applying these types of methods in determination of optimum planting date.

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