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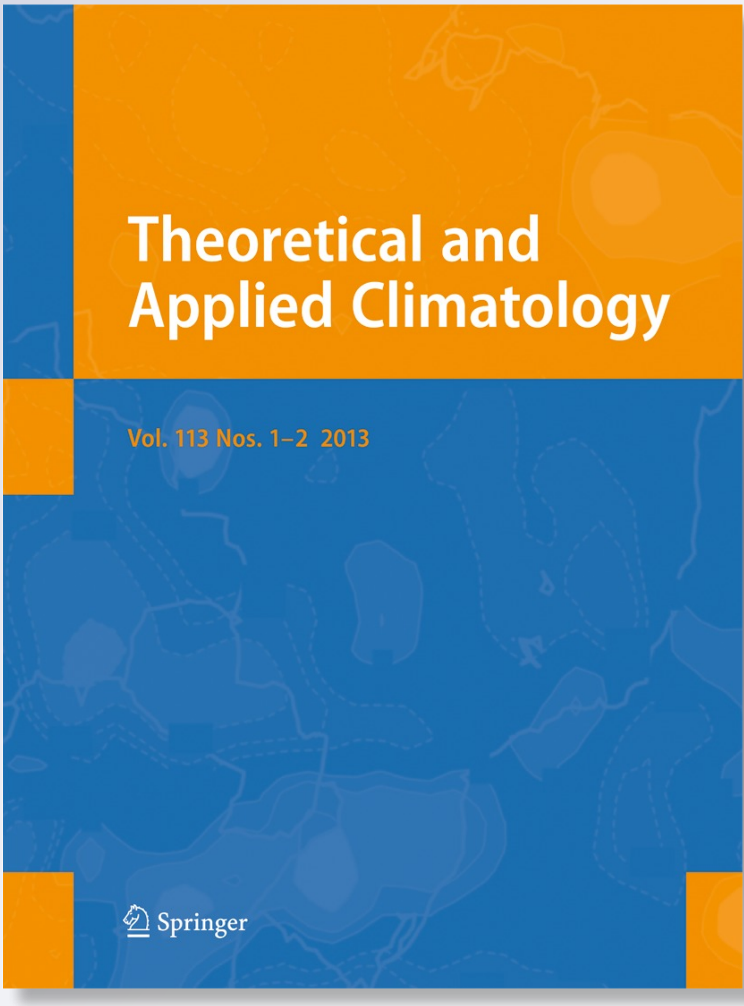

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ORIGINAL PAPER

Agrometeorological study of crop drought vulnerability and avoidance in northeast of Iran

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Abstract Drought is one of the crucial environmental factors affecting crop production. Synchronizing crop phenology with expected or predicted seasonal soil moisture supply is an effective approach to avoid drought impact. To assess the potential for drought avoidance, this study investigated the long-term climate data of four locations (Bojnourd, Mashhad, Sabzevar, and Torbat Heydarieh) in Khorasan province, in the northeast of Iran, with respect to the four dominant crops (common bean, lentil, peanut, and potato). Weekly water deficit defined as the difference between weekly precipitation and weekly potential evapotranspiration was calculated. Whenever the weekly water deficit was larger than the critical water demand of a crop, the probability for drought was determined. Results showed that Sabzevar has the highest average maximum temperature (24.6 °C), minimum temperature (11.7 °C), weekly evapotranspiration (32.1 mm), and weekly water deficit (28.3 mm) and has the lowest average weekly precipitation (3.8 mm). However, the lowest mean maximum temperature (19.7 °C), minimum temperature (6.9 °C), weekly evapotranspiration (22.5 mm), and weekly water deficit (17.5 mm) occur in Bojnourd. This location shows the shortest period of water deficit during the growing season for all crops except potato, which also experienced drought at the end of the growing season. Sabzevar and Torbat Heydarieh experienced the highest probability of occurrence and longest duration of drought during the growing season for all crops. The result of this study will be helpful for farmers in order to reduce drought impact and enable them to match crop phenology with periods during the growing season when water supply is more abundant.

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1 Introduction

Drought is one of the major natural disasters in the world, and more than half of the earth is susceptible to drought each year (Kogan 1997; Wilhelmi and Wilhite 2002). The climate has always presented a challenge to those whose livelihoods depend on it (Hellmuth et al. 2009); hence, drought is very costly in societies that are dependent on subsistence agriculture (FAO 2004). Occurrence and intensity of drought are gradual, cumulative, and so slow that they are not easily realized (Unganai and Kogan 1998). It is sometimes difficult to quantify drought in terms of spatial extent and intensity (Mkhabela et al. 2010). Furthermore, drought has broadly been categorized as being a meteorological, hydrological, agricultural, or socioeconomic issue (Unganai and Kogan 1998; Heim 2002; Mkhabela et al. 2010). There are many definitions of agricultural drought, and generally, it has been defined as any season with low rainfall in relation to crop water demand that results in poor crop harvest or total crop failure (Giunta et al. 1993; Bannayan et al. 2010; Araya and Stroosnijder 2011). In arid and semi-arid regions, crops are mostly rainfed, and the sowing date of crops depends upon the rainfall. Therefore, drought is an ever-present risk (Hellmuth et al. 2009). In these regions, farmers must be equipped with a variety of crop management approaches to deal with water deficit resulting from the soil, weather, or limited irrigation (Debaeke and Aboudrare 2004). These approaches can be categorized into six objectives: (1) increasing soil-stored water at plant sowing, (2) increasing soil water extraction, (3) reducing the contribution of soil evaporation of total water use, (4) optimizing the seasonal water use pattern between pre- and post-crop anthesis, (5) tolerating water stress and recovering after stress alleviation, and (6) irrigating at the most sensitive growth phases. Thus, drought impacts may be avoided by synchronizing crop phenology with expected or predicted seasonal soil moisture supply or when water supply is likely to be more abundant (Purcell et al. 2003; Blum 2009). Anthesis and grain filling are the most sensitive stages among crop development stages to drought (Farah et al. 1988; Johansen et al. 1989).

Determination of the optimum planting date plays a vital role in the avoidance of the sensitive crop phenological stages to face drought. Soler et al. (2008) and Bassu et al. (2009), by using a modeling approach, determined the optimum planting date for millet and wheat, respectively. Traditional techniques have also been widely used to determine the optimum planting date (Ati et al. 2001). Because of the inability to provide a feed-forward approach to avoid drought through these techniques, Purcell et al. (2003), by using long-term weather data, developed an analytical and statistical approach that can be used to evaluate the probability of drought from a cropping perspective. Based on their approach, drought stress for a given crop can be determined by means of weekly precipitation and evapotranspiration. Therefore, in any given location, by determining the time when a crop will be exposed to drought stress, the risk avoidance strategies such as changing the sowing date or planting different cultivars with a shorter growing season can be employed. Under such conditions, the negative impact of drought can be minimized, and crops can avoid the drought.

Iran, a country with an area of 1,648,000 km^2, is located in the southwest of Asia with arid and semi-arid climates. During the summer season, most parts of Iran are hot and arid, and during winter, they are cold. The major portion of precipitation occurs between November and May, and then the warm dry season prevails. The annual mean precipitation during the past 50 years in Iran was about 240 mm (Kousari et al. 2010; Bannayan et al. 2010). In Iran, the major amount of precipitation occurs in winter, but most crops are cultivated in spring. Therefore, crop production level depends on preserved soil moisture and on the occurrence of terminal drought at the end of the crop growing season. In fact, water deficit causes major yield reductions of rainfed farms, and the most severe water deficit occurs during the crop reproductive phase (Bannayan et al. 2011a). Water deficit and unsuitable distribution of precipitation are the most important local challenges that hinder the development of agriculture and sustainability of products. In such conditions, crop production and mostly rainfed production systems show the most fluctuations in productivity (Bannayan et al. 2011b). Such conditions occurred in 2008 in Iran when precipitation was 42 % lower than the historical annual average, and about 95 % of rainfed farms severely suffered (Ministry of Jihad-e-Agriculture Iran 2009).

The objective of the current study was to determine the periods that crops will be exposed to drought stress using the means of long-term weather data in the northeast of Iran. We also compared the vulnerability of four regional dominant agricultural crops and determined susceptible periods within the growing season for each study crop.

2 Materials and methods

2.1 Study site and weather data

The study area, Khorasan province, is located in the northeast of Iran and lies between 38 ° S and 30 ° N latitude and 55 ° W and 61 ° E longitude, a semi-arid location with an area of 248,000 km^2. Khorasan province has a long history of drought of various geographic extents, severities, and durations (Table 1).

Historical daily weather data of four different locations (Bojnourd, Mashhad, Sabzevar, and Torbat Heydarieh) across the study area were collected from the meteorological station at each location. These included maximum and minimum temperatures (°C), sunshine hours (h), relative humidity (%), wind speed (ms^{-1}), and precipitation (mm) which were also used to calculate the reference crop evapotranspiration (ETo), based on the FAO Penman–Monteith method (Allen et al. 1998). The required calculation was based on the 44-year daily weather data of Mashhad (1961–2005) and 23-year daily weather data (1982–2005) of Bojnourd, Sabzevar, and Torbat Heydarieh. Homogenization of weather data was performed

Table 1 Physiographic details of study locations

Location	LA (°N)	LN (°E)	Elev (m)	Average minimum temperature (°C)	Average maximum temperature (°C)	Total precipitation (mm)	Climate data period
Bojnourd	37.27	57.18	1,210	6.9	19.6	265	1982–2005
Mashhad	36.16	56.36	999	8.3	21.6	256	1961–2005
Sabzevar	36.13	57.37	940	11.8	24.7	197.8	1982–2005
Torbat Heydarieh	35.16	59.13	1,450	7.5	20.4	267.6	1982–2005

LA latitude, *LN* longitude, *Elev* elevation by the national meteorological organization of Iran (www.weather.ir) before the release of such data to users.

2.2 FAO Penman–Monteith equation

Potential evapotranspiration is defined as the theoretical amount of water lost through evapotranspiration from a closed canopy of green grass of uniform height, actively growing, completely shading the ground, and with adequate soil moisture, conductance, and albedo (Allen et al. 1998). The FAO Penman–Monteith equation can be further derived from standard crop parameters through the following relationship for daily reference crop evapotranspiration (Smith 2000):

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma\left[\left(\frac{890}{T+273}\right)\right]U_2 \times VPD}{\Delta + \gamma(1 + 0.34U_2)}, \tag{1}$$

where ETo is the reference crop evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJM^{-2} d^{-1}), G is the soil heat flux (MJM^{-2} d^{-1}), T is the average air temperature (°C), U_2 is the wind speed measured at a 2-m height (ms^{-1}), VPD is the vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve (kPa°C^{-1}), γ is the psychometric constant (kPa°C^{-1}), and 890 is the conversion factor. The full details of the FAO Penman–Monteith equation have been published in the FAO Irrigation and Drainage Paper No.56 (Allen et al. 1998). In the absence of wind speed measurements, the FAO procedure suggests using a value of 2 ms^{-1}(Allen et al. 1998).

A 7-day water deficit for each Julian day of each study year was estimated by the difference between the 7-day cumulative ETo and the 7-day cumulative precipitation. Summing the precipitation, the ETo, and water deficit variables over 7-day periods was based on the method employed by Virmani et al. (1982) and Purcell et al. (2003).

2.3 Transpirational water use efficiency

Transpirational water use efficiency (WUE; Pa kPa^{-1}) was estimated based on the method employed by Tanner and Sinclair (1983), Purcell et al. (2003), and Gholipoor and Soltani (2008).

$$WUE = K \times CVPD^{-1} \tag{2}$$

$$CVPD = (e_{\max} - e_a) \times 0.75 \tag{3}$$

$$e_{\max} = 0.6108 \times \exp(17.27 \times T_{\max})/(T_{\max} + 237.3) \tag{4}$$

$$e_a = 0.6108 \times \exp(17.27 \times T_{\min})/(T_{\min} + 237.3), \tag{5}$$

where e_a is the actual water vapor pressure and e_{max} is the maximum water vapor pressure. CVPD (kPa) refers to the weighted daily VPD experienced by crops during transpiration.

Considerable evidence illustrates a narrow correlation between the accumulation of plant weight (W) and the amount of water evaporated from leaves (i.e., transpiration, T). Atmospheric VPD and K are two variables which thoroughly describe the correlation between W and T. The parameter K is a species-dependent water use constant, and the atmospheric VPD defines the moisture content of the atmosphere. The value of K depends upon some of the same factors which influence WUE. Compared to C_3 crops, K is higher for the C_4 photosynthetic pathway and high-carbohydrate plant material. Maximum values for K have been estimated by both theoretical derivation and experimental results (Tanner and Sinclair 1983). The maximum value of K for maize is about 11 kPa, for rice about 6 kPa, and for soybean about 5 kPa. In general, the value of K is approximately 5 kPa for C_3 plants (Tanner and Sinclair 1983). WUE was calculated using the same approach (Eq. 2) for the total growing season for each location.

2.4 Critical water deficit

Water deficit level, in which a crop reveals decreased growth and yield, primarily depends upon the rooting depth (Sinclair and Muchow 2001; Purcell et al. 2003). If an approximate rooting depth (mm) for a location is known, then the total amount of available soil water (ASW; mm) for plants may be estimated as the product of the rooting depth and the value of 0.13 (Sinclair et al. 1998; Purcell et al. 2003). The water supply is 0.13 which is the difference between soil water volumetric content at field capacity and water content when plants experience severe water stress (permanent wilting point (PWP)) (Ratliff et al. 1983; Sinclair et al. 1998; Purcell et al. 2003). Plants typically begin to tolerate water deficit stress when approximately 0.65 of the ASW has been depleted (Ray and Sinclair 1998; Purcell et al. 2003). Therefore, Purcell et al. (2003) calculated a critical water deficit (CWD; mm) in which plants begin to experience water deficit stress as shown below:

$$CWD = D \times 0.13 \times 0.65, \tag{6}$$

where D is the rooting depth (mm). In this study, the volumetric water content at field capacity (FC) and volumetric water content at PWP were estimated by means of pedotransfer functions (PTFs), and then, the difference between FC and PWP as ASW was used instead of the value of 0.13 for each location.

2.4.1 Pedotransfer functions

There are many attempts to estimate soil water content based on soil parameters to quantify the water availability. Direct measurement of soil hydraulic properties on a large spatial scale is relatively time-consuming, labor-intensive, and expensive (Lakzian et al. 2010). In addition, the results may not be accurate due to spatial and temporal variability in soil physical and hydraulic properties (Merdun et al. 2006). Indirect estimation of hydraulic properties from widely available or more easily measured basic soil properties (sand, silt, clay, bulk density, and organic matter) can also be considered as an alternative. Pedotransfer functions have received considerable attention (Wosten et al. 1995; Minasny and McBratney 2002; Minasny et al. 2004; Merdun et al. 2006). A pedotransfer function is a mathematical relationship between two or more relatively easily collected soil parameters, such as soil texture, bulk density, and organic matter content (Bouma and Van Lanen 1986; Gupta and Larson 1979; Lakzian et al. 2010). The general equation is as follows:

$$\theta = a\,sand + b\,silt + c\,clay + d\,organic\,content, \tag{7}$$

where θ is the water content (m^3m^{-3}) at a specific soil water potential (kPa); a, b, c, and d are regression coefficients. These regression coefficients are different for field capacity and permanent wilting point. PTFs validated and calibrated by Lakzian et al. (2010) in the northeast of Iran for FC and PWP were employed in this study.

Critical water deficit was calculated for four crops (lentil, common bean, potato, and peanut) for each location (Table 2). The probability of the 7-day water deficit (drought) exceeding the critical water demand was calculated for each location for each day of each year.

Table 2 Critical water deficit values (mm) for four crops in the study locations

Crop	Study locations			
	Bojnourd	Mashhad	Sabzevar	Torbat Heydarieh
Common bean	52.6	52.2	36.7	41.6
Lentil	61.4	60.9	42.8	48.5
Peanut	61.4	60.9	42.8	48.5
Potato	43.9	43.5	30.5	34.7

3 Results and discussion

The time duration between the last frost (minimum temperature below 0 °C) in spring and the first frost in autumn was determined as the growing season. This frost-free period was used as the growing season in four different locations in Khorasan province (Table 3). Using this approach, the length of the growing season was 219 days for Bojnourd (north of Khorasan province), 221 days for Mashhad, and 217 days for Torbat Heydarieh (center of Khorasan province). The length of the growing season for Sabzevar was 256 days (west of Khorasan province). Although there were no significant differences between the length of the growing season in the north and central regions, the length of the growing season was higher in the west region (Sabzevar) because it is close to the central desert of Iran and is drier than the north and central parts of Khorasan. In this location, the occurrence of the last frost in spring is earlier than in the north and central parts, and the occurrence of the first frost in autumn is later.

The average maximum and minimum temperatures of all days of a year and during the growing season and the weekly evapotranspiration and weekly water deficit of all days of a year and during the growing season did not indicate considerable discrepancy in Bojnourd, Mashhad, and Torbat Heydarieh; however, Sabzevar showed differently (Table 4). Sabzevar showed the highest values of maximum temperature (24.6 °C), minimum temperature (11.7 °C), weekly evapotranspiration (32.1 mm week^{-1}), and weekly water deficit (28.3 mm week^{-1}) and the lowest weekly precipitation (3.8 mm week^{-1}) over the entire year. The lowest values of maximum temperature (19.7 °C), minimum temperature (6.9 °C), weekly evapotranspiration (22.5 mm week^{-1}), and weekly water deficit (17.5 mm week^{-1}) of the entire year were for Bojnourd. Furthermore, Bojnourd showed the lowest annual average of solar radiation (16.5 MJ m^{-2} d^{-1}), and Torbat Heydarieh indicated the highest annual average value of solar radiation (18.5 MJ m^{-2} d^{-1}). A similar trend was also found for the growing season as part of the year. As expected,

Table 3 Occurrence of 0 °C minimum temperature at the beginning and end of the growing season and duration of the growing season

Location	0 °C T_{min} occurrence		Duration of the growing season (days)
	Last (DOY)	First (DOY)	
Bojnourd	88	307	219
Mashhad	85	306	221
Sabzevar	75	332	256
Torbat Heydarieh	87	304	217

DOY day of the year, T_{min} minimum temperature

Table 4 Historical values of the minimum and maximum temperatures, solar radiation, 7-day precipitation, 7-day evapotranspiration, and 7-day water deficit for four locations during a year and during the growing season

Location	T_{max} (°C)	T_{min} (°C)	Radiation ($MJ m^{-2} d^{-1}$)	Precipitation ($mm week^{-1}$)	ETo ($mm week^{-1}$)	Water deficit ($mm week^{-1}$)
Averaged over a year						
Bojnourd	19.71	6.94	16.54	5.02	22.55	17.53
Mashhad	21.35	7.26	17.51	5.28	23.53	18.16
Sabzevar	24.6	11.74	17.84	3.78	32.13	28.30
Torbat h	20.6	7.55	18.54	5.37	26.27	20.94
Averaged over the growing season						
Bojnourd	26.77	12.3	20.79	4.06	31.32	27.25
Mashhad	28.31	12.7	21.59	3.78	32.77	29.08
Sabzevar	30.17	15.42	20.80	2.33	40.39	38.06
Torbat h	23.3	6.6	22.92	2.71	37.44	34.75

T_{min} minimum temperature, T_{max} maximum temperature

Bojnourd, which is located in the north of Khorasan province, showed a cooler temperature and lower evapotranspiration and radiation than Mashhad, Torbat Heydarieh, and Sabzevar which are located in the central and western Khorasan province. Compared to other locations, Sabzevar showed warmer weather and thus higher evapotranspiration (Table 4).

Weekly water deficit values gradually increased for 200 days of a year, and after that, they showed a slow decrease for all locations (Fig. 1a). The values of the 7-day water deficit were estimated based on the difference between the 7-day cumulative ETo and 7-day cumulative precipitation. Whenever precipitation was lower than ETo, the value of the water deficit increased. Therefore, the

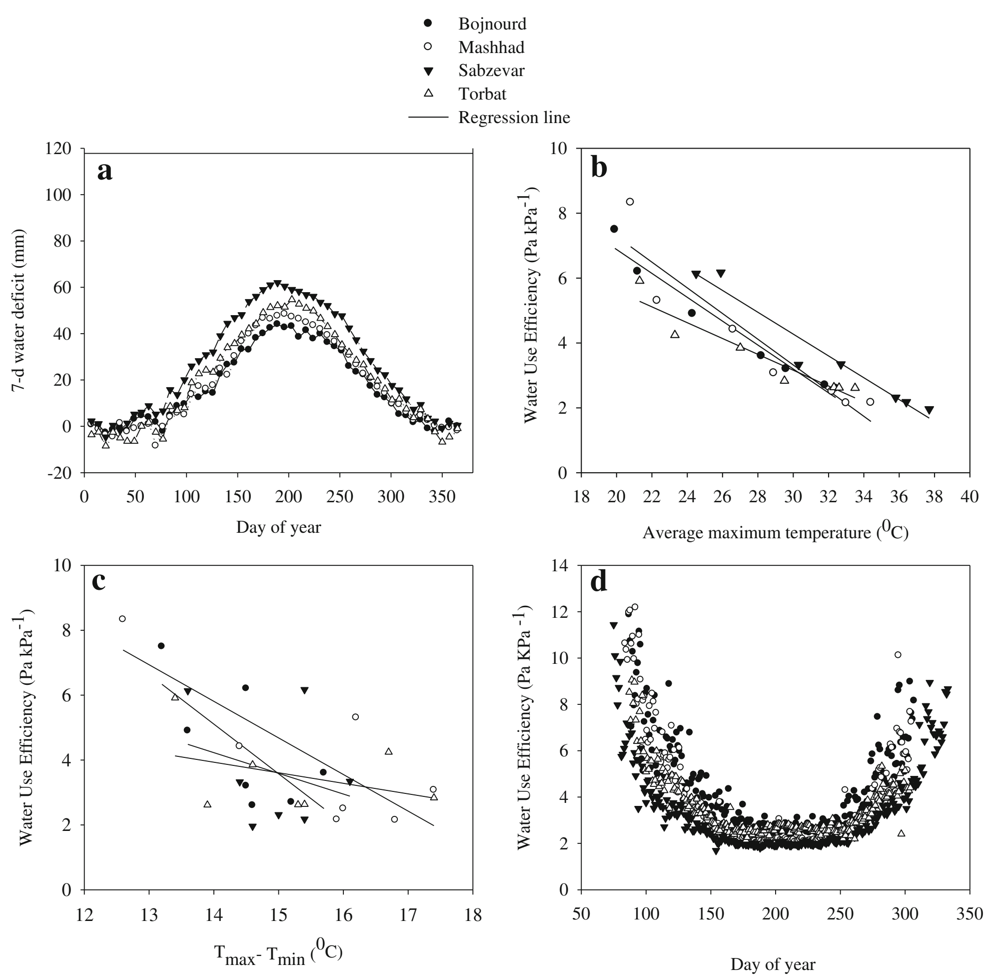

Fig. 1 Cumulative weekly water deficit over the year (**a**), relationship between the historical average values of the water use efficiency and the maximum temperature during the growing season (**b**), relationship between the historical average values of water use efficiency and difference between the maximum and minimum temperatures during the growing season (**c**), and the average water use efficiency during the growing season (**d**) for Bojnourd, Mashhad, Sabzevar, and Torbat Heydarieh

Table 5 Planting dates and the length of growing season for four crops in the northeast of Iran

Crop	Planting date (DOY)	Growing season (days)
Common bean	107–114	120–130
Lentil	93–113	90–100
Peanut	100–110	150–165
Potato	100–120	90–180

DOY day of the year

values of the 7-day water deficit depend on precipitation and temperature during the growing season.

A significant correlation was found between the average water use efficiency and the average maximum temperature during the growing season (Fig. 1b). A negative correlation between the average water use efficiency and the average maximum temperature was also obtained across all locations. Water use efficiency decreased by increasing the average maximum temperature in all locations. The highest correlation (r=0.96) between the water use efficiency and the maximum temperature was found in Bojnourd and Sabzevar, respectively. Moreover, because of meteorological effects on water availability for crop production, the ability of crops to utilize water for biomass production changes in response to environmental conditions which in turn determine the water use efficiency (Purcell et al. 2003). Because e_{max} increases exponentially with the maximum temperature (Eq. 3), small changes in the maximum temperature have large effects on the water use efficiency. The values of VPD reflect the environment in which the crop is growing. In humid regions, the value of VPD is low, and in arid regions, it is high. One approach to decrease the value of VPD in arid regions is to grow the crop during the cooler months when VPD is low. However, there was no significant correlation between the water use efficiency and the difference between the maximum and minimum temperatures, except in Mashhad (r=0.65) (Fig. 1c).

The highest values of WUE (>8 PakPa^{-1}) were obtained at the beginning of the growing season (day of the year (DOY) 75–88) and at the end of growing season (DOY 304–332), and the lowest values of WUE (<4 Pa kPa^{-1}) were obtained at the mid of the growing

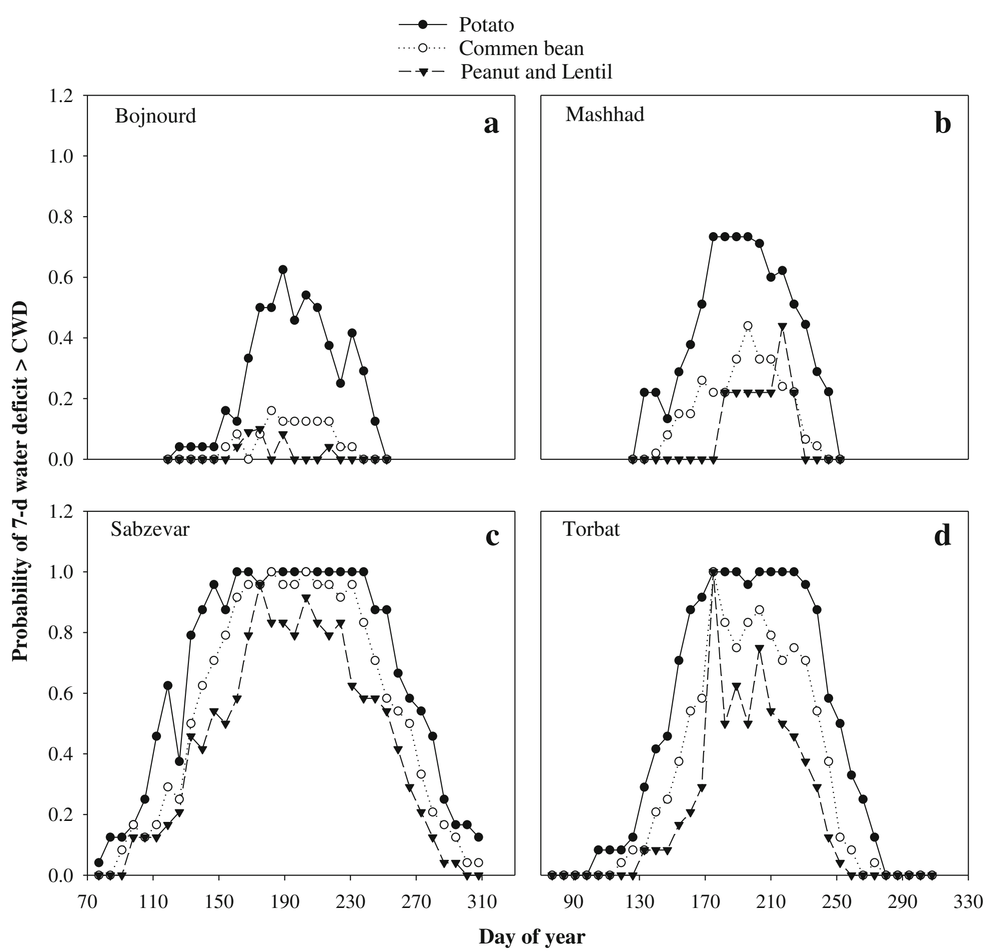

Fig. 2 Cumulative probability of weekly water deficit is higher than critical water demand during the growing season for common bean, lentil, peanut, and potato for Bojnourd (**a**), Mashhad (**b**), Sabzevar (**c**), and Torbat Heydarieh (**d**)

season for all locations (Fig. 1d). Generally, for the four crops (common bean, lentil, peanut, and potato), the planting date is between DOY 93 and DOY 140, and the length of the growing season is from DOY 180 to DOY 300 (Table 5).

The calculated drought probability represented that at all locations, all the crops during the growing season confronted drought, but the timing, intensity, and duration of drought were different (Fig. 2). In fact, Fig. 2 is a magnified window of Fig. 1a, which is calculated through the critical water demand for each crop (Table 2). Between DOY 150 and DOY 180, the probability of drought occurrence gradually increased for potato in Bojnourd (Fig. 2a). In addition, the probability of drought occurrence was low for common bean, peanut, and lentil during the growing season. In addition, the probability of drought occurrence slightly declined between DOY 180 and DOY 250 for common bean, lentil, and peanut; however, such decline was sharper for potato. In general, because of the cooler weather in Bojnourd, the drought occurrence probability and duration were lower than those in the other locations. In Mashhad, the probability of drought enhanced rapidly between DOY 120 and DOY 180 for potato, and it maintained at the same level between DOY 180 and DOY 210 and then diminished quickly (Fig. 2b). The rate of the increasing probability of drought for common bean was slower than that for potato between DOY 120 and DOY 200, and it declined slightly between DOY 200 and DOY 240 (Fig. 2b). For lentil and peanut, the highest probability of drought was between DOY 180 and DOY 220 in Mashhad. In Sabzevar, the probability of drought grows significantly for potato and common bean between DOY 70 and DOY 150, and it remained constant between DOY 150 and DOY 250; after that, it decreased sharply. For lentil and peanut, the probability of drought increased rapidly between DOY 90 and DOY 180, and it dropped dramatically between DOY 180 and DOY 310 (Fig. 2c). Torbat revealed a similar trend (Fig. 2d). In general, Sabzevar and Torbat experienced the highest probability of drought (100 %) and the longest duration (100 and 50 days), respectively.

To validate this study approach, the actual rainfed yield of the study crops (lentil, common bean, peanut, and potato) was investigated for 20 historical years for all locations. The results illustrated that farmers could not achieve any rainfed yield in Sabzevar and Torbat due to the high probability of drought during the growing season for all crops. However, lentil produced an acceptable rainfed yield during these years in Bojnourd and Mashhad. Due to the high water requirement, potato is not under rainfed cultivation in Bojnourd and Mashhad, and peanut is not in the cultivation schedule in all locations (Fig. 3).

4 Conclusion

In this study, the probability of drought during the growing season was investigated by means of long-term climate data for common bean, lentil, peanut, and potato in the northeast of Iran in four locations (Bojnourd, Mashhad, Sabzevar, and Torbat Heydarieh). This study revealed a high risk of drought for Sabzevar and Torbat for all crops. For instance, in Sabzevar, the probability of drought occurrence between DOY 150 and DOY 170 is 100 %, and the conventional planting date of common bean and potato in this region takes place between DOY 107 and DOY 114 and between DOY 100 and DOY 120, respectively. Thus, part of the growing season of these two crops will coincide with drought. Ludlow and Muchow (1990) remarked that intermittent and terminal droughts are two possible patterns of

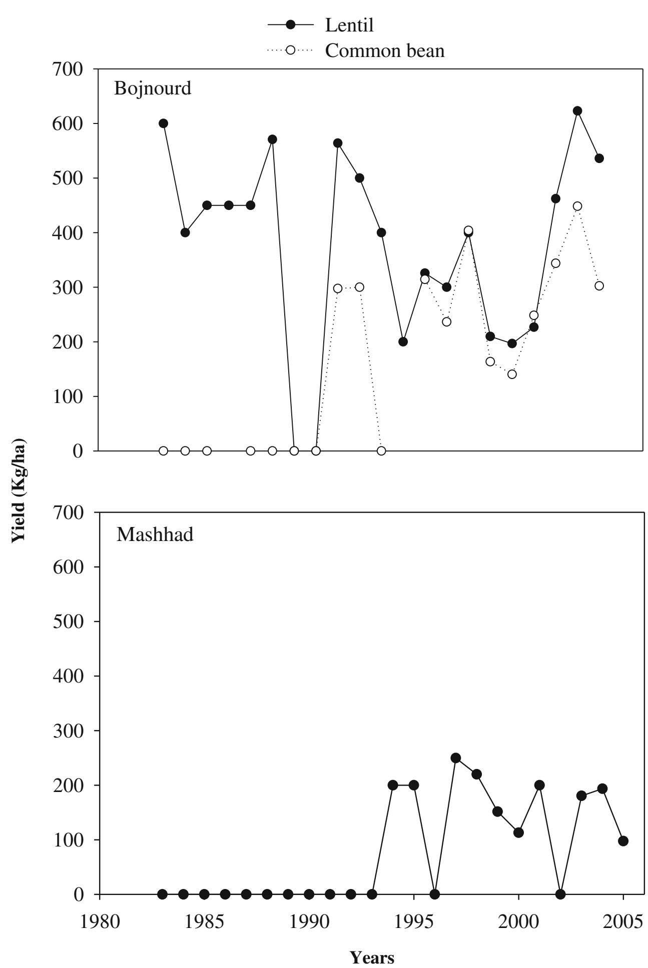

Fig. 3 Observed yields of common bean and lentil during 20 historical years for Bojnourd and Mashhad

water stress. In intermittent drought, stress can occur at any time and with various intensities between emergence and maturity, while terminal drought occurs where the crop grows and matures on a progressively depleted soil moisture profile. Intermittent stress is observed in most of the regions of Western and Central Europe where short periods of drought are observed in spring and summer, affecting occasionally autumn-sown crops but more regularly spring-sown and long-season crops. Terminal drought, on the other hand, characterizes the low rainfall of Mediterranean-type environments. Crop growth is limited to a short winter growing season which starts with autumn rainfall and ends with declining soil moisture and high temperatures in spring (Cooper et al. 1987; Debaeke and Aboudrare 2004). Therefore in this study, in Sabzevar, the optimum planting date should be matched to optimize the capture of water available because anthesis which is a sensitive period can avoid the water stress. The results also explored that the environmental conditions in Bojnourd are so favorable for crop production if water deficit is compensated by irrigation.

Using this approach, one could determine the timing of drought occurrence during the growing season, and farmers can avoid drought. They can match crop phenology with periods during a growing season when water supply is more abundant. Hence, adopting an earlier planting date and using short growing season cultivars or supplementary irrigation might help to avoid the drought.

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