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Dryland farming improvement by considering the relation between rainfall variability and crop yield

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Abstract

About 40% of the global cultivable land practices dryland farming. An improvement of dryland farming is imperative to ensure food security for expanding populations in the developing world. This paper presents a method to assess the impact of precipitation variability on the annual yield of dryland farmed crops. All probable periods of precipitation in three dryland farming seasons (autumn, winter, and spring) are considered. The effect of each period of precipitation on the annual yield of dryland farmed crops is assessed, and the most effective period of precipitation on the annual yield of each crop is identified. Subsequently, annual yield versus effective precipitation regressions for each crop are developed. The annual crop yields are calculated with annual yield versus effective precipitation regressions and with the probability distribution function method. The presented methodology is illustrated with an application to wheat and barley production in Hamedan Province, Iran. The most effective period of precipitation for predicting the annual yield of dryland farmed wheat and barley in all conditions is March 30–May 7. The predictive skill of the annual yield versus effective precipitation regressions is evaluated and found to yield crop yield estimates that are very similar to those obtained with the probability distribution function method.

Keywords Dryland farming · Precipitation changes · Effective precipitation–annual yield (EP-AY) regression

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1 Introduction

Dryland farming is a widespread type of cultivation, especially in water-scarce countries. Dryland farming efficiency depends on several factors such as soil and crop types, furrow and mulching methods, and precipitation that have been studied in in previous works. Zhang et al. (2013) evaluated yield and water use efficiency of wheat cultivation in the dryland area of the Loess Plateau of China. They relied on 20-year data and compared conventional practices with alternatives showing that yield and the water use efficiency (WUE) ranged from 818 to 7900 kg ha^{-1} and from 3.4 to 23.4 kg ha^{-1} mm^{-1}, respectively. Wang et al. (2016) evaluated microfield rain harvesting farming system in Kenya which has the potential to increase profitability and productivity of dryland wheat in arid and semiarid countries such as eastern Asia. Their results showed that mulching treatments increased wheat grain yield by 60–163%, decreased the evapotranspiration by 11.4–88.5 mm, and enhanced water use efficiency by 68–271%.

Precipitation is the main determinant of dryland farming. It is the source for the consumptive water use of crops in addition to soil moisture. The seasonal and annual total potential evapotranspiration exceeds the precipitation in drylands, and dryness has increased in many dry regions with climatic change (Huang et al. 2016; Lickley and Solomon 2018; Wu and Chen 2019). Zhang et al. (2016) reported an eco-hydrological model which predicts that for a given annual rainfall there are positive correlations between the rainfall intensity and deep soil moisture and woody vegetation cover. Therefore, an increase in rainfall may lead to an increase in deep soil moisture and woody vegetation cover given relatively uniform annual rainfall regime in dryland ecosystems. Hadi Pour et al. (2020) assessed the spatial and temporal changes in annual and seasonal aridity in Iran in the 1951–2016. They assessed the relation between rainfall and temperature with aridity in various arid zones to understand the driving factors climatic shifts in arid lands. Their results indicate an expansion of arid lands in Iran due to increasing annual and seasonal aridity. Also, a decrease in rainfall was the cause of the increasing aridity in the arid and semiarid regions, while the increasing temperature was the main cause of increasing aridity in the humid region.

Precipitation variability during the farming season largely determines the dryland farming crop yields. Thus, it is imperative to know how the timing and amount of precipitation affect dryland farming crop yields as a prerequisite to improve this agricultural practice. Gibbs and Maher (1967) developed a method of precipitation analysis to explore relations between precipitation changes and drought indicators. Edwards (1979) introduced the method of precipitation quartile analysis. McKee et al. (1993) developed a method called the standardized precipitation index (SPI), which detects drought and its severity. The precipitation–deviation index method has been applied to monitor the variability of precipitation in semiarid regions such as in northeastern Brazil (Hastenrath 1984; Hastenrath et al. 1984) and southern Africa (Katz 1978; Hulme 1992).

Mollah and Cook (1996) investigated precipitation changes and the impacts of those changes on arid and semiarid farming lands of northern Australia. Results showed that annual precipitation increased while the trend of precipitation changed within the study region. These patterns of precipitation called for adaptation in the timing of the planting and harvesting seasons. Sadras et al. (2003) studied the profitability of farming in the Mallee region of Australia based on different cropping strategies and the region's precipitation. Noohi (2005) determined the best time for dryland farming cultivation in the Karaj region of Iran based on precipitation analysis. Wimalasuriya et al. (2008) investigated the relation between precipitation changes and dryland farming production in the State of Victoria, Australia. Results showed that the short-term mean of annual precipitation is highly variable and thus is one of the indicators of drought in the region. The profitability of dryland farming varied between regions and between years and depends on changes in the crop patterns.

Previous works have analyzed dryland farming under various conditions such as types of furrow, mulching methods, soils types, and crop types. This paper assesses the impact of precipitation variability on the yield of dryland farmed wheat and barley in autumn, winter, and spring in Hamedan Province, Iran. This assessment is helpful for decision makers for the purpose of determining and predicting the crops' yields and managing future agricultural activities. The relation between the effective period of precipitation and the annual crop yield is also determined leading to regression functions of crop yield versus effective precipitation. The effective precipitation is that which produces the best crop yield. The annual yields of dryland farmed wheat and barley were calculated with the crop yield versus precipitation regressions and with probability distribution functions of crop yield derived from historical yield data.

2 Methods and materials

Four gauging stations (Hamedan airport, Ghorveh, Nahavand, and Malayer) were chosen to analyze precipitation in Hamedan Province, Iran (Fig. 1), where the dryland farmed area equals 1.5 times the area under irrigation. The Ghorveh, Malayer, and Nahavand stations are located in dryland farmed areas, while the Hamedan airport station is at the center of Hamedan Province in a non-cultivated area. Ghorveh station was chosen as a base station for analysis because of its location in the largest dryland farmed region. Thus, Ghorveh station provided the precipitation data with which to calculate the mean precipitation, the total precipitation, and the maximum precipitation during periods of various lengths for the purpose of determining the effective period of precipitation governing the annual yield of

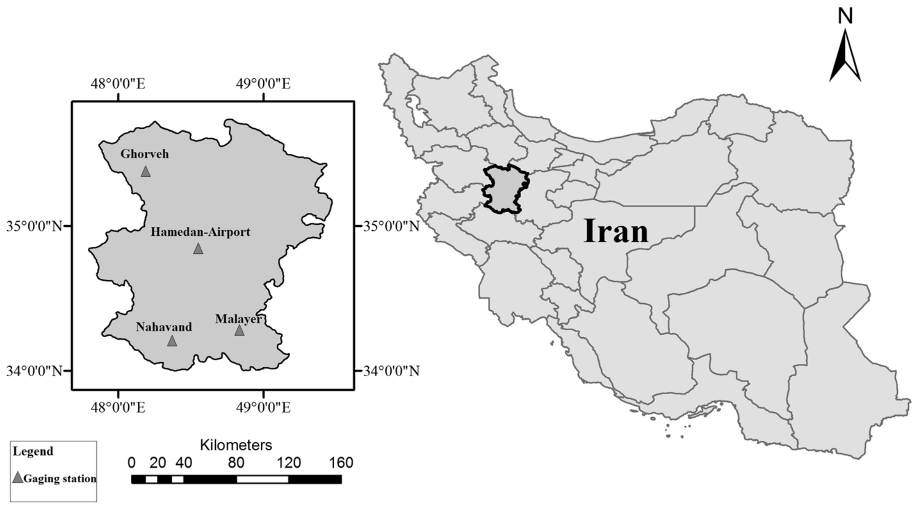

Fig. 1 Map of four gauging study stations in Hamedan Province of Iran

dryland farmed wheat and barley. It is also worth mentioning that wheat and barley have growing periods equal to 240 and 219 days, respectively, encompassing autumn, winter, and spring seasons (Allen et al. 1998).

Daily precipitation data for the Ghorveh station were aggregated by converting daily precipitation data to 1-day, 2-day, 3-day,…., 30-day precipitation series. Each one of these 30-time series was then used to calculate the mean precipitation, the total precipitation, and the maximum precipitation. The correlation coefficients (R^2) of the regressions between the annual yield of dryland farmed wheat and barley and the precipitation parameters (mean, total, and maximum) were calculated for 17 years of 1993–2009. The precipitation variable with the best R^2 was chosen as the effective precipitation variable with which to estimate crop yield. Regressions between crop yield (the predicted variable) and crop effective precipitation (the predictor variable) were calculated for each of the 30 times series associated with the mean precipitation, the total precipitation, and the maximum precipitation, for a total to 90 regressions for wheat and 90 regressions for barley.

The effective precipitation for the annual yield of each crop was determined with frequency analysis, from which the predictive skill of the crop yield versus precipitation regressions was assessed. The best probability distribution function (PDF) corresponding to historical data of effective precipitation was selected from the frequency analysis. The empirically derived cumulative distribution functions (CDFs) were applied to obtain the effective precipitation (with a 5% significance level). The effective precipitations from the CDFs were substituted into the regressions of crop yield versus precipitation. These regressions produced estimates of the annual yield of dryland farmed wheat and barley.

As an alternative approach, the annual yield of each crop was estimated from the probability distribution function (PDF) of crop yields. For this purpose, historical data of the annual yield of each crop were subjected to frequency analysis. The empirical PDFs and CDFs of the annual yield of each crop were separately calculated, and the annual yields of dryland farmed wheat and barley were estimated for various probability levels. These yields obtained directly from PDFs were considered as the best estimates of the annual yield of dryland farmed products and were compared with the yields derived from the crop yield versus precipitation regressions.

In summary, the annual yields of dryland farmed wheat and barley were calculated by two methods. The first method is the crop yield versus precipitation regressions, which is based on specified probabilities of effective precipitation. The second method employed the empirically derived probability distribution functions corresponding to the historical annual yield of dryland farmed wheat and barley.

2.1 Determination of the suitable precipitation parameter

Daily precipitation data at the Ghorveh station were aggregated into each time period and expressed in terms of the mean, total, and maximum precipitation. Table 1 lists the number of precipitation periods based on their correlation coefficient with the annual yield of dryland farmed wheat and barley.

The maximum precipitation has the lowest positive correlation with the annual yields of dryland farmed wheat and barley. The total and mean precipitations have nearly equal correlation with and the annual crop yields. As for data aggregation, the mean precipitation measures the impact and magnitude of precipitation of all days in a period. That is, if rain does not occur on some days of a period, then this parameter measures the impact of no-rain days. Also, if errors occur in recording the magnitude of daily precipitation, then these errors are distributed

Table 1 Correlation R^2 (%) between precipitation parameters (mm) and the annual yield of wheat and barley by dry farming (kg/ha)

Correlation coefficient (R^2)	Percentage of time intervals					
	Wheat			Barley		
	Mean	Total	Max	Mean	Total	Max
(0.8)–(0.9)	0.00	0.00	0.00	0.00	0.02	0.02
(0.7)–(0.8)	45.78	48.19	6.02	0.18	0.49	0.45
(0.6)–(0.7)	36.18	35.75	28.07	1.69	1.52	1.40
(0.5)–(0.6)	29.59	29.52	40.89	6.20	5.28	5.09
(0.4)–(0.5)	34.67	34.63	30.70	57.80	9.78	9.34
(0.3)–(0.4)	32.74	32.91	34.35	8.69	9.86	9.11
(0.2)–(0.3)	30.71	30.89	38.40	14.98	12.59	12.15
(0.1)–(0)	33.25	33.10	33.64	10.99	10.37	10.59
(0)	33.76	33.36	32.87	16.52	14.90	14.56
(−0.1)–(0)	32.34	32.21	35.45	12.34	10.40	10.52
(−0.2)–(−0.1)	33.33	33.13	33.64	6.61	7.38	7.99
(−0.3)–(−0.2)	36.02	35.95	28.03	4.92	6.76	7.68
(−0.4)–(−0.3)	38.42	38.42	23.16	4.44	5.97	6.25
(−0.5)–(−0.4)	31.96	31.81	36.16	4.09	3.91	4.31
(−0.6)–(−0.5)	36.36	40.91	22.72	0.39	0.25	0.38
(−0.7)–(−0.6)	50.00	50.00	0.00	0.03	0.09	0.11

among the days in the considered period by using the mean precipitation. This makes the mean precipitation a suitable parameter for aggregating daily data and also for assessing the relation between precipitation and the annual yield of dryland farmed wheat and barley.

2.2 Determination of the most effective precipitation period on the annual yield of dryland farmed wheat and barley

The mean precipitation was chosen as a suitable parameter for aggregating precipitation. The regressions function between the annual yield of each crop and the mean precipitation in three seasons (autumn, winter, and spring) were calculated. The correlation coefficients (R^2) between mean precipitation in different periods and the annual yield of dryland farmed wheat and barley were calculated and assigned as indicators of the goodness of fit. The annual yield versus effective precipitation regressions and their correlation coefficient (R^2) were calculated with the Minitab 15 software (Minitab Inc. 2007) to choose the most effective precipitation period concerning the annual yield of dryland farmed wheat and barley at each climatic station. The regressions are given by Eqs. (1) and (2) for wheat and barley, respectively:

$$Y_w = a + bX_f + cX_w + dX_s \tag{1}$$

$$Y_b = a + bX_f + cX_w + dX_s \tag{2}$$

where Y_w and Y_b are, respectively, the annual yield of dryland farmed wheat and barley (kg/ha), X_f, X_w, and X_s are the mean precipitation in autumn, winter, and spring, respectively (mm) and *a*, *b*, *c* and *d* are constants.

The spring mean precipitation has on average the largest impact on annual yield of dryland farmed wheat and barley (Table 2). The impacts of autumn and winter mean precipitations were assessed based on location and the climate of the gauging stations. A more detailed examination of precipitation during the cultivation seasons (October 1-July 31) is presented in Fig. 2, which shows the correlation between mean precipitation calculated over periods of 5, 10, 15, 20, 25, and 30 days and the annual yield of dryland farmed wheat at the Ghorveh, Hamedan airport, Malayer, and the Nahavand stations. Similar illustrations showing the correlation of mean precipitation over periods of 5, 10, 15, 20, 25, and 30 days and the annual yield of dryland farmed barley at the aforementioned stations are included in Fig. 3.

The dryland farmed wheat is cultivated in October and November. Therefore, the first precipitations from the beginning of November to the middle of December affect wheat yield significantly. The relation between mean precipitation and wheat yield remains strong until the beginning of January. During January 1–31, the relation between precipitation and yield begins to decline. During April 14-May 15, the trend of correlation coefficient between mean precipitation and annual yield increased dramatically, thus showing that precipitation in this period also affects the yield of wheat significantly. Similarly, precipitations corresponding to November and December have a significant impact on the annual yield of barley. There is a high correlation between mean precipitation in November and from the beginning of December to late January and the annual yield of barley. The highest correlation between mean precipitation and the annual yield of barley occurs from late April to the middle of May. In other words, during this period, precipitation has the largest impact on the annual yield of barley. Thus, the correlations between mean precipitation and the annual yield of barley follows a trend similar to that of the annual yield of wheat. The only difference is that the trend of correlation between mean precipitation and the annual yield varies more in barley than in wheat. The reason for this variability is the natural characteristic of dryland farmed barley, which is more resistant to water stress. As a result, the correlation between precipitation and the annual yield of barley is less significant than in wheat. In general, there are two time periods with the largest impact on the annual yield of dryland farmed crops: the first period is from late December to the beginning of January, and the second period is in the spring (from late April

Table 2 Regression functions between the annual yield of dryland farmed wheat and barley and seasonal mean precipitation at four climatic stations

Station	Crop	Regression function between the annual yield and the seasonal mean precipitation	(R^2)
Ghorveh	Wheat	$Y_w = 515 + 2.22X_f + 0.26X_w + 1.06X_s$	32.8%
	Barley	$Y_b = 516 + 3.41X_f + 0.88X_w + 1.05X_s$	32.2%
Hamedan airport	Wheat	$Y_w = 317 + 0.95X_f + 0.75X_w + 3.90X_s$	37.1%
	Barley	$Y_b = 253 + 1.41X_f + 1.94X_w + 4.39X_s$	29.8%
Malayer	Wheat	$Y_w = 226 + 1.14X_f + 1.67X_w + 4.81X_s$	68.1%
	Barley	$Y_b = 34 + 2.53X_f + 3.14X_w + 5.47X_s$	60.7%
Nahavand	Wheat	$Y_w = 159 + 0.43X_f + 1.70X_w + 5.02X_s$	73.2%
	Barley	$Y_b = 34 + 1.23X_f + 2.35X_w + 6.05X_s$	70.6%

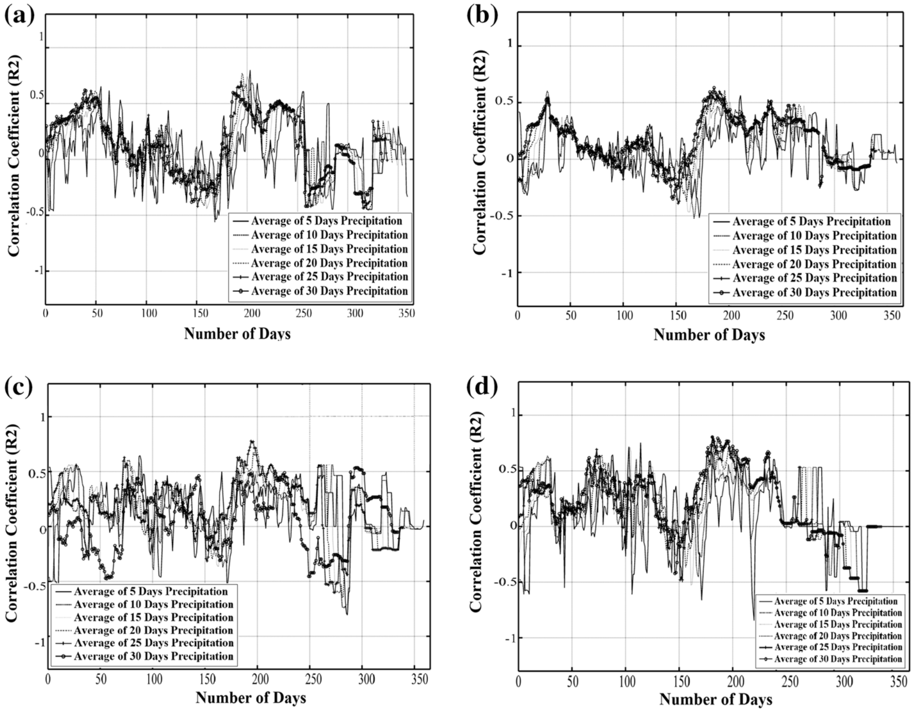

Fig. 2 Mean precipitation correlation in different periods with the annual yield of dryland farmed wheat at the: **a** Ghorveh, **b** Hamedan airport, **c** Malayer, and **d** Nahavand stations

to late May). However, our results indicate that the most effective precipitation period on the annual yield of wheat and barley occurs in the spring. Also, the autumn precipitations had considerable larger effect on the annual yield of wheat and barley than winter precipitations at the Ghorveh and Hamedan airport stations, located in a northern, relatively colder region. In contrast, the winter precipitations had more effect on the annual yield of wheat and barley than the autumn precipitation at the Malayer and Nahavand stations, located in a southern, more temperate region. Therefore, it appears that the impact of autumn–winter precipitations on the annual yield of dryland farmed products depends on the regional climate.

2.3 Determination of the annual yield versus effective precipitation regressions (EP-AY) of dryland farmed wheat and barley

The most effective period of mean precipitation on the annual yield of wheat and barley at each station was chosen as explained in the previous section. The regression functions between effective mean precipitation and the annual yield were then determined for each crop. Equations 3 and 4 indicate the respective annual yield versus effective precipitation regressions of dryland farmed wheat and barley.

$$Y_w = aX^2 + bX + c \tag{3}$$

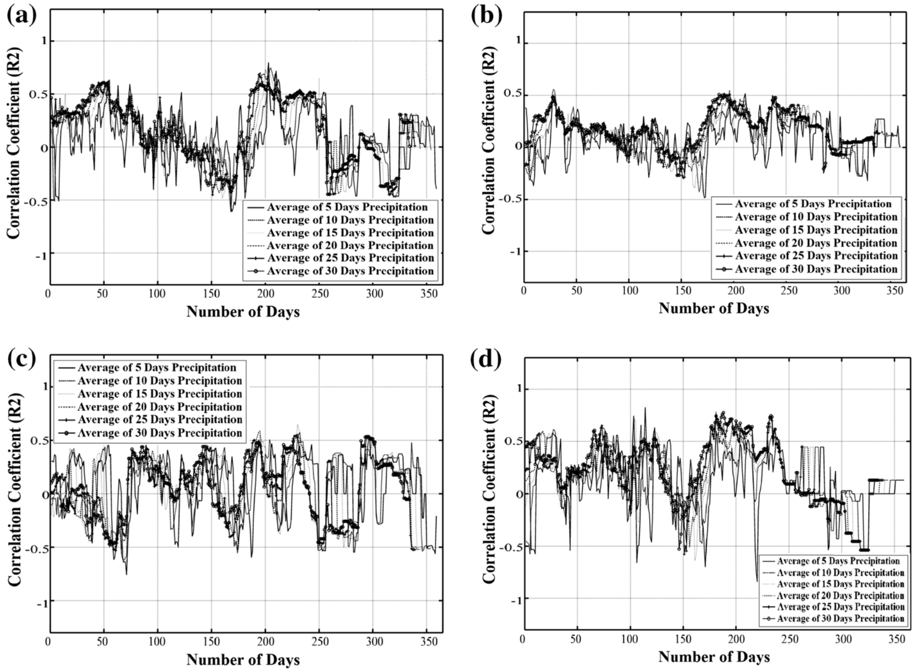

Fig. 3 Mean precipitation correlation in different periods with the annual yield of dryland farmed barely at the: **a** Ghorveh, **b** Hamedan airport, **c** Malayer, and **d** Nahavand stations

$$Y_b = aX^2 + bX + c \tag{4}$$

where X is the mean precipitation of the most effective period of precipitation (mm). Table 3 lists the most effective period of mean precipitation on annual yield and the regression functions EP-AY for wheat and barley at the four gauging stations.

Table 3 Effective period of mean precipitation for the annual yield of dryland farmed wheat and barley

Station	Crop	The effective period of mean precipitation	(R^2)	Regression function annual yield versus mean precipitation
Ghorveh	Wheat	April 22 until May 4	0.61	$Y_w = -4.31X^2 + 254.60X + 700.08$
	Barley	April 22 until May 4	0.54	$Y_b = -5.74X^2 + 197.53X + 584.92$
Hamedan airport	Wheat	March 30 until May 2	0.43	$Y_w = -28.13X^2 + 316.83X + 404.19$
	Barley	March 30 until May 2	0.31	$Y_b = -89.47X^2 + 577.77X + 363.98$
Malayer	Wheat	March 30 until May 6	0.68	$Y_w = -56.49X^2 + 487.09X + 322.19$
	Barley	April 6 until May 7	0.63	$Y_b = -146.29X^2 + 877.52X + 179.05$
Nahavand	Wheat	March 30 until May 4	0.81	$Y_w = -60.55X^2 + 525.10X + 41.17$
	Barley	March 30 until May 4	0.77	$Y_b = -99.48X^2 + 775.79X + 40.336$

2.4 Assessment of annual yield versus effective precipitation regressions for wheat and barley

The probability distribution functions corresponding to the mean precipitation in the effective period specified for each crop at each station were determined based on the Kolmogorov–Smirnov criteria with the EasyFit 3 software (Math Wave Technologies 2006). The distribution functions corresponding to mean precipitation for each effective period were determined, and, thereafter, the precipitation depths in the effective period were estimated for the specified probabilities. Those depths were inserted in the regression functions between effective precipitation and the annual yield listed in Table 3. The annual yields of wheat and barley were estimated with the EP-AY regressions.

The predictive skill of the calculated annual yield versus effective precipitation regressions was evaluated by applying the probability distribution function method to the historical data of annual yield of dryland farmed wheat and barley. The best distribution function corresponding to the annual yield of each crop, based on the Kolmogorov–Smirnov criteria and by using EasyFit 3, was chosen to estimate the annual yield of dryland farmed wheat and barley, for the specified probabilities. All calculations were based on a non-exceeding 5% probability. Figures 4 and 5 depict the annual yield of dryland farmed wheat and barley, respectively, by considering the aforementioned methods at the Ghorveh, Hamedan airport, Malayer, and Nahavand stations. It is seen in Figs. 4 and 5 that the estimates of annual yield of dryland farmed wheat and barley by using the annual yield versus effective precipitation

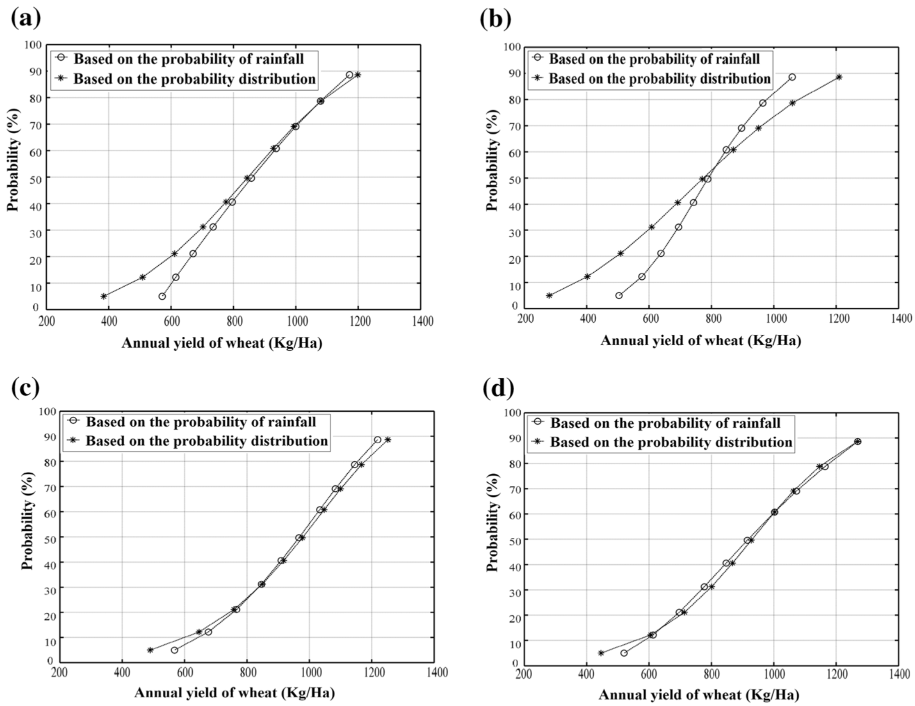

Fig. 4 Probability of annual yield of dryland farmed wheat at the: **a** Ghorveh, **b** Hamedan airport, **c** Malayer, and **d** Nahavand stations

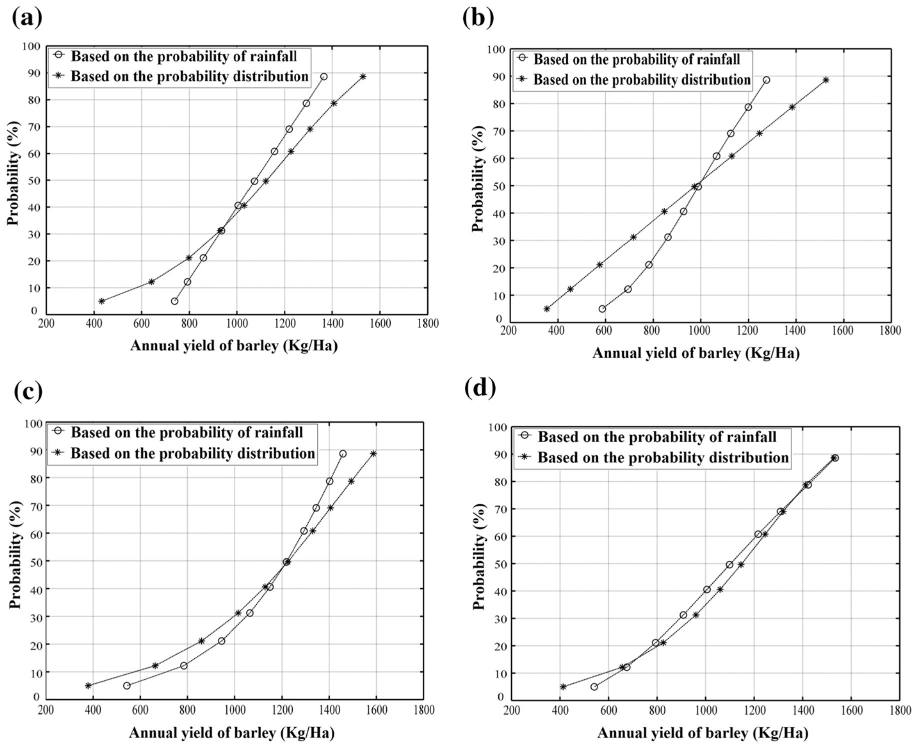

Fig. 5 Probability of annual yield of dryland farmed barley at the: **a** Ghorveh, **b** Hamedan airport, **c** Malayer, and **d** Nahavand stations

regressions are similar those obtained with the distribution function corresponding to the crops' historical annual yields. Thus, our results indicate an accurate predictive skill of the annual yield versus effective precipitation regressions (that were developed on the basis of the effective period of precipitation) in estimating the annual dryland farmed yield. The average correlation coefficient of the annual yields estimated by regression and with the probability distribution function method equaled 99.3%.

3 Concluding remarks

Monitoring of the impact of more than 90 series of precipitation on the annual yields dryland farmed wheat and barley in Hamedan Province, Iran, revealed that the mean precipitation parameter, rather than the total or maximum precipitation, is best to analyze the impact of precipitation variability on the yield of those two crops. Our results demonstrate that the precipitation occurring in April to May has the most impact on the annual yields of dryland farmed wheat and barley. It was also recognized that the value and importance of autumnal and winter precipitation concerning the annual yield of dryland farmed crops depend on the prevailing regional climate. An analysis of the trend of precipitation and the annual yield of dryland farmed crops indicates that precipitation is more significant on wheat than on barley. Regression functions between the effective precipitation and the annual crops' yields produced similar estimates of crops' yields as those obtained with the probability distribution functions of crops' yields. The correlation coefficient between the results obtained with the two methods (i.e., regressions and probability distribution functions) was, on average, 99.3%. This demonstrates the accuracy of the annual yield versus effective precipitation regressions in estimating the annual yield of crops. This study established a positive statistical association between the yields of dryland farmed wheat and barley and precipitation, although the correlation with precipitation was found to be lower for dryland farmed barley. Dryland farmed barley is best adapted to arid areas, and the effect of precipitation on the yield of wheat is more pronounced on wheat than on barley in the study area. It is worth mentioning that precipitation falling in different stages of the growing period of crops influences the annual yield, and this constitutes an area of research deserving future attention.

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Compliance with ethical standard

Conflict of interest All authors declared that they have no conflict of interest.

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