Full Paper

Journal of Agricultural Meteorology 74(4): 162-172, 2018

Determining agricultural drought for spring wheat with statistical models in a semi-arid climate

Funian Zhao[a, b, c,†], Jun Lei[d], Runyuan Wang[a], Heling Wang[a], Kai Zhang[a] and Qiang Yu[e,f]

[a] Key Laboratory of Arid Climatic Change and Disaster Reduction of Gansu Province, Key Laboratory of Arid Climate Change and Disaster Reduction of CMA, Lanzhou Institute of Arid Meteorology, China Meteorological Administration, Lanzhou 730020, China

[b] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

[c] University of Chinese Academy of Sciences, Beijing 100049, China

[d] Dingxi Meteorological Bureau, Dingxi 743000, China

[e] State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling 712100, Shaanxi, China

[f] College of Resources and Environment, University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Agricultural drought frequently occurs and results in major grain yield loss in semi-arid climate region, but determining it is difficult. This study was conducted to determine agricultural drought for spring wheat (*Triticum aestivum* L.) in the western Loess Plateau of China. Several statistical models were established and evaluated by long-term data, including soil water in soil layer of 50 cm depth at sowing day, air temperature, precipitation, pan evaporation during spring wheat growing season, and two groups of spring wheat yield (one from field experiments during 1987-2011 and the other from statistical Bureau during 1980-2013). Even though each of water supply factors, precipitation during growing season and the soil water at sowing day, could separately explain no more than 30% variation of the yield, both of them could explain >55% yield variation under dry condition. Average air temperature and precipitation during growing season that displayed two apparent yield categories (drought and normal) could be used to determine agricultural drought by pattern recognition when years with the soil water at sowing day of >98.4 mm were eliminated. Based on long-term meteorological data and the relationship between soil water at sowing day and yield under different growing season moisture conditions, the probability of agricultural drought occurrence in Dingxi for spring wheat was speculated, which nearly corresponds with the observational data during 1980-2013.

Key words: Pattern recognition, Precipitation, Regression analysis, Soil water content, Yield

1. Introduction

Crop growth and final yield are generally determined by environmental factors, such as solar radiation, temperature, water, nutrition, pests, diseases, and weeds (Yu *et al*., 2014). In fact, the latter four factors are easy to control by field management, but the first three factors at optimal level are difficult to obtain. Semi-arid areas have an apparently climatic characteristic labeled as cold winter, warm summer, and small amount but highly erratic precipitation. Although high temperature also could result in yield loss in semi-arid areas, dryland crop production is heavily depended on available water (Nielsen *et al*., 2009), and agricultural drought frequently occurs in these areas.

A universally accepted definition of drought does not exist as consideration of multiple disciplines (Wilhite, 1993). For agricultural drought, it is always defined as a reoccurring and complex phenomenon caused by lack of adequate water in soil during crop growing season, resulting in significant yield loss (Panu and Sharma, 2002). Therefore, deviation from average yield of a primary crop is usually used to define occurrence of agricultural drought in a research region (Kumar and Panu, 1997). At present, researchers have developed two common approaches to simulate crop yield and thereafter used them for determining agricultural drought, statistical models (regression models for instance), and process-based models, such as crop models (Gouache *et al*., 2015). Although the latter one is identified as mechanistic model developed rapidly worldwide, the statistical model is still very useful in many areas, especially in the regions lacking adequate data to calibrate parameters for process-based models.

Generally, researchers use data obtained from weather stations during crop growing season, for instance, temperature, precipitation, evaporation, wind velocity, and radiation hours singly or jointly (Wu *et al*., 2011), to determine the occurrence of agricultural drought using statistical models. However, many of the statistical models, such as drought indices, had been criticized for lacking steady relationship with crop yield in different research areas. Moreover, some other new methods,

Received; February 24, 2018
Accepted; July 27, 2018
†Corresponding Author: zhaofn@iamcma.cn
DOI: 10.2480/agrmet.D-18-00011

based on machine learning (such as pattern recognition), have been seldom validated in different areas of the world.

Among these statistical models, the simple relationship between yield and water use is probably the best indicator to determine yield loss and, therefore, agricultural drought occurrence. However, the amount of water usage for crop is related not only to the weather status during crop growing season but also to the soil water storage before crop sowing (Nielsen *et al*., 2002). Lyon *et al*. (1995) showed that the soil water at sowing day explained 40%−80% variation of spring-planted crop yield, especially for short season crops. On the other hand, many researchers use available water, which is the sum of soil water in a specific depth of soil profile at sowing day and precipitation during crop growing season, to deal with water and crop yield relations (Schillinger *et al*., 2008). Furthermore, crop final yields always have significant linear relationships with total amount of water use in arid and semi-arid climates (Huang *et al*., 2004; Nielsen, 1997). The amount of precipitation during crop growing season is easy to obtain from an adjacent weather observation station. However, the time series of soil water at sowing day in a specific depth of soil profile, ranging from 1.8 to 2 m as per many previous studies (Li *et al*., 2004; Nielsen *et al*., 2015; Stone and Schlegel, 2006), is limited during a long term. Therefore, with limited data, it is difficult to obtain a precise relationship between water use and crop yield in many areas.

In the western Loss Plateau of China, a typical semi-arid region, spring wheat is one of the most popular sowed crops (Huang *et al*., 2005). However, with a fluctuated precipitation during growing season, the farmers in this area recently are reluctant to cultivate spring wheat. They choose to plant potato and corn with plastic, which can obtain relatively higher amount of precipitation during growing seasons (Qin *et al*., 2013). Meanwhile, using plastic, it also could save much water in soil by preventing evaporation (Zhang *et al*., 2008). Nevertheless, spring wheat is still a very important cereal for this region. How to obtain higher yield for spring wheat avoiding an agricultural drought and conducting a series of managements to timely deal with agricultural drought before spring wheat harvest are very important. Therefore, the objectives of this study were (1) to establish several statistical models based on environmental factors to help determine agricultural drought in this area and (2) to compare these models and use the most accurate one to speculate the probability of agricultural drought occurrence in this semi-arid area.

2. Materials and Methods

2.1 Site description

The studies were conducted in a semi-arid region, Dingxi (104°12′−105°01′E, 35°17′−36°02′N, 1898.7 m a.s.l. in average), Gansu province, Northwest of China. Average annual precipitation in this area is approximately 386 mm, whereas 60% of the annual precipitation occurs from July to September. Only approximately 30% of precipitation falls during spring wheat growing season (March−June). Distribution of precipitation during spring wheat growing season is highly erratic, and the average coefficient of variation is approximately 32.5% (Table 1). Meanwhile, no irrigation equipment is used for spring wheat in this area. The soil type in this area is a typical loessial soil, pertained to sandy loam (60% sand), with low organic content and very high infiltration rates and is easy to cultivate. The soil in the 0 to 50 cm layer has an average bulk density of 1.3 g cm^{-3}, a field capacity of 0.251 cm^3 cm^{-3}, and a wilting point of 0.058 cm^3 cm^{-3}.

2.2 Data collection

Two groups of spring wheat yield were collected. One was from field experiment (FE). The FE was conducted during 1987−2011 at the Dingxi agro-meteorological experimental station (35° 35′ N, 104° 36′ W, 1898 m elevation above sea level), affiliated to the Chinese Meteorological Administration. The experimental cropland was divided into four plots. Each plot size was 10 × 25 m, with north−south row direction. Spring wheat was typically planted in middle- to late-March and harvested in middle- to later- July. The main varieties of spring wheat planted in this area were Weichun1, 81139, Longchun20, and Dingxi New24 during 1987−2011 (Table 2). Maturity types of these varieties were middle and middle-late. The seeding rate ranged from 187.5 to 225.0 kg ha^{-1}, with farmyard manure ranging from 15000 to 35000 kg ha^{-1} and nitrogen fertilizer from 42 to 104 kg N ha^{-1} (1987−2011) before spring wheat sowing. Under water-limited condition, water is always the most limited factor for plant production, and fertilizer has little impact on plant production until water supply surpasses a specific threshold (Ponce *et al*., 2013; Li *et al*., 2017). Meanwhile, we found there was no increasing trend of spring wheat yield as nitrogen supply increased during 1987−2011 (see next paragraph for details). Therefore, we had not taken the impact of varying fertilizer levels on spring wheat yield into account in our analysis. At harvest, all spring wheat plants in the experimental field were

Table 1. Statistical data of soil water content at sowing day, precipitation, pan evaporation, air temperature during growing season (March−June), and experimental and statistical yield for spring wheat from 1987 to 2011.

Variables	Maximum	Minimum	Average	Standard deviation	Coefficient of variation (%)
Soil water content at sowing day (mm)	125.9	51.2	94.3	19.6	20.8
Precipitation (March–June) (mm)	204.2	48.9	133.5	43.4	32.5
Air temperature (March–June) (℃)	12.4	9.1	10.7	0.85	8.0
Pan evaporation (March–June) (mm)	685.9	487.6	577.3	51.9	9.0
Experimental yield (kg ha^{-1})	3373.7	310.0	1655.5	897.0	53.8
Statistical yield (kg ha^{-1})	2104.5	499.5	1278.5	474.7	39.1

Table 2. Sowing and fertilizing details for spring wheat in the Dingxi agro-meteorological experimental station (1987−2011).

Year	Variety	Maturity	Seeding rate (kg seeds ha^{-1})	Fertilizer	
				Farmyard manure (kg ha^{-1})	(kg N ha^{-1})
1987–1991	Weichun1	Middle-Late	187.5−225.0	15000−35000	42.0−104.0
1992–1998 2000	81139	Middle-Late			
1999	92 Jian46	Middle			
2001	Dingxi35	Middle			
2002 2005–2006 2008–2011	Dingxi New24	Middle			
2003–2004	Longchun20	Middle			
2007	MY94-9	Middle-Early			

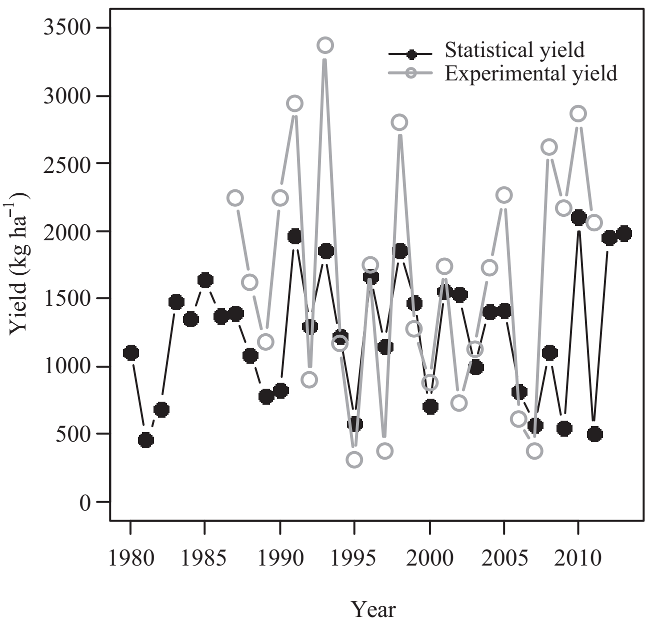

Fig. 1. Variations of statistical yield and experimental yield during 1980−2013 at Dingxi in the western Loess Plateau, China.

collected, and the actual grain yield was measured at four replicated square meters. Then, their average was multiplied by 10000 to obtain the actual yield in 1 ha. The other group of spring wheat yield data from 1964 to 2013 was obtained from Dingxi Bureau of Statistics (DBS). The main cultivars from 1980 to 2013 released to the farmers in Dingxi were nearly identical to the varieties used in the FE, whereas we had not collected the information about the cultivars used from 1964 to 1979.

We found that the data of DBS during 1964−1979 were significantly lower than those from 1980 to 2013 (average yield is 795.7 versus 1249.4 kg ha^{-1}), probably because of an apparent genetic improvement after 1979. Therefore, we eliminated this range of yield data. Meanwhile, to evaluate the possibility of improvement in yielding ability through breeding effect or fertilizer level increase for FE during 1987−2011 and data of DBS from 1980 to 2013, simple linear regression between spring wheat yield and year was adopted. However, no confidence was placed on there being changes in spring wheat yield potential over the years for the two data groups (with linear model significance level $p > 0.1$) (Fig. 1). Hence, we did not make adjustments in yield of the two groups of data for an increasing yield trend that results from genetic improvement in our efforts to determine agricultural drought in this area.

Daily precipitation, surface air temperature, and open pan evaporation from 1960 to 2013 were measured at a weather station approximately 100 m from the plot area in the Dingxi agro-meteorological experimental station. Monthly precipitation, pan evaporation, and average air temperature were computed. Amount of precipitation and pan evaporation during growing season of spring wheat was the sum of precipitation and pan evaporation during March−June each year (Table 1). The precipitation, average air temperature, and pan evaporation during spring wheat growing season from 1987 to 2013 are shown in Fig. 2.

Soil water content for FE was measured from 1987 to 2011 at sowing day each year in four plots by gravimetric sampling at 10 cm depth intervals up to 50 cm depth. Gravimetric soil water content at 0 to 50 cm soil profile was converted into volumetric water content by multiplying the soil bulk density in each layer. Total water content in 50 cm depth of soil profile was then calculated in each plot. The average soil water of the four replicated plots was used in this study (Fig. 2d).

2.3 Agricultural drought occurrence definition

Agricultural drought usually occurs when soil water availability to plants in a specific area has dropped to a level (threshold) that is insufficient for crop development, growth, and maturation and thus adversely affects the final crop yield (Mannocchi *et al*., 2004). However, the onset, duration, and severity of agricultural drought are quite difficult to determine. In quantitatively defining agricultural drought, one way is commonly used based on the deviation from the mean yield of a major crop in a study area. Therefore, percentage reduction from the long-term mean yield can be selected, and agricultural drought is considered to have occurred if final crop yield is below the given threshold (Kumar *et al*., 1998). Various thresholds of percent deviation from the mean yield exist, and we selected 75% of mean yield data of FE and DBS as the threshold of agricultural drought occurrence (1100 kg ha^{-1}),

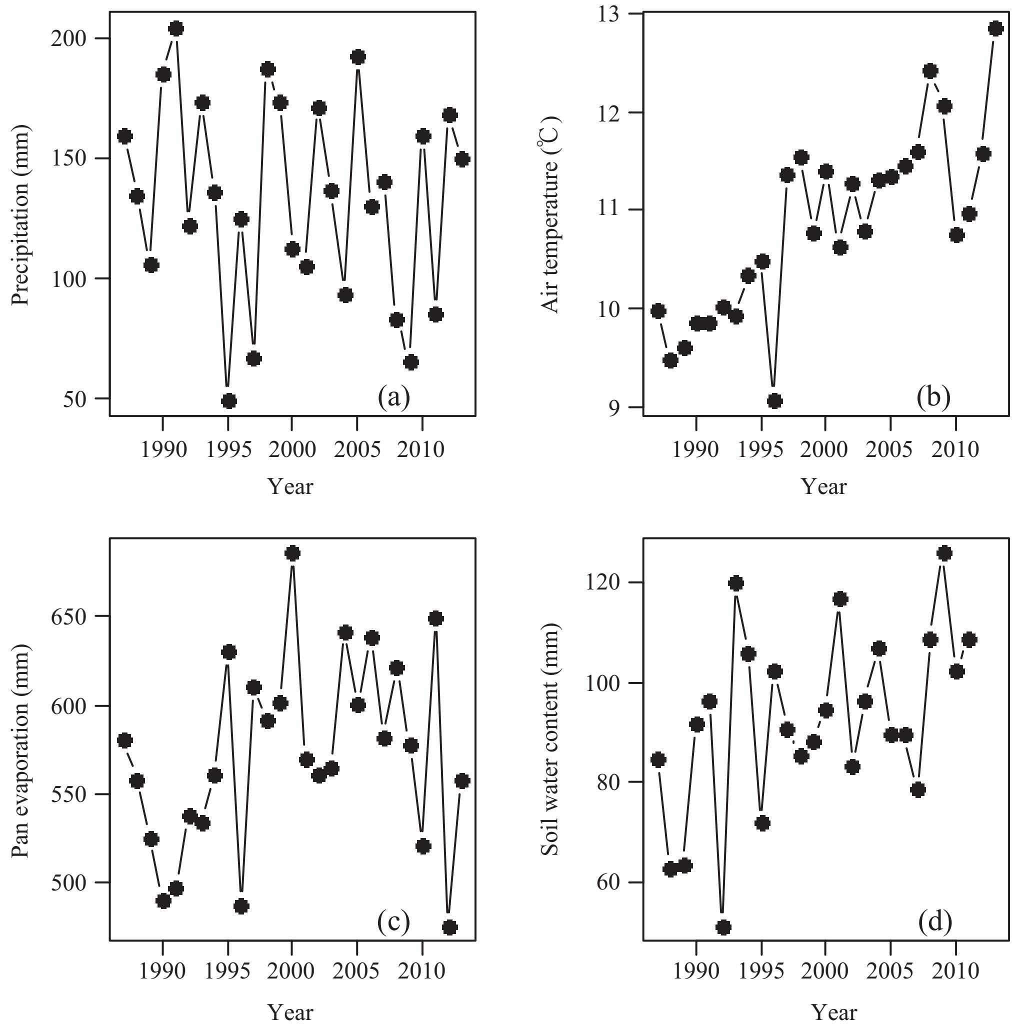

Fig. 2. Data of environmental factors at Dingxi during 1987–2013 for (a) precipitation from March to June, (b) average air temperature from March to June, (c) pan evaporation from March to June, and (d) soil water content at sowing day.

which classified the degree of agricultural drought as mild-to-moderate level (Kumar and Panu, 1997).

2.4 Statistical analysis

To determine the occurrence of agricultural drought based on environmental factors using statistical models, the data of FE were used to establish statistical models because of its detailed observation information (including agricultural manage practice, soil water content at sowing day, and time of growth stages). Meanwhile, because water is the primary limited factor for spring yield in the study area, the data of DBS with different agricultural management practices and longer term compared with those of FE could confirm the accuracy and validity of the statistical models. Therefore, the data of DBS were applied for statistical models validation. Two main types of models were adopted in this study. One was linear regression, and the other one was pattern recognition.

2.4.1 Linear regression methods

The relationships among soil water at sowing day and yield, precipitation during spring wheat growing season and yield, and sum of soil water and precipitation and yield were analyzed by simple linear regression. Multiple linear regression was used to analyze the response of yield to both soil water content and precipitation. Simple and multiple linear regression analysis were completed by functions of "lm" and "summary" in the programming language R (R Development Core Team, 2014).

2.4.2 Pattern recognition

Pattern recognition is a type of cluster method. It is used to classify objects into different categories based on specific characteristics. Pattern recognition can be used in multiple areas, such as signature identification, medical engineering, and speech recognition (Boken *et al*., 2007). For weather forecast, it is usually used to predict weather condition based on relations between data and weather categories in historic records. In this research, we had two main categories, drought and normal, based on a threshold of 75% of mean spring wheat yield. We used two climatic factors, which are easy to obtain for forming the vector of spring wheat yield category in this study.

The liner equation we aimed to obtain is as follows:

$$g(x) = w^T x \quad (1)$$

where $g(x)$ is the equation used to determine agricultural drought for spring wheat; w^T is a solution vector, in the form of $w(w_1, w_2)$ at two dimensions; and x is category vector, formed at

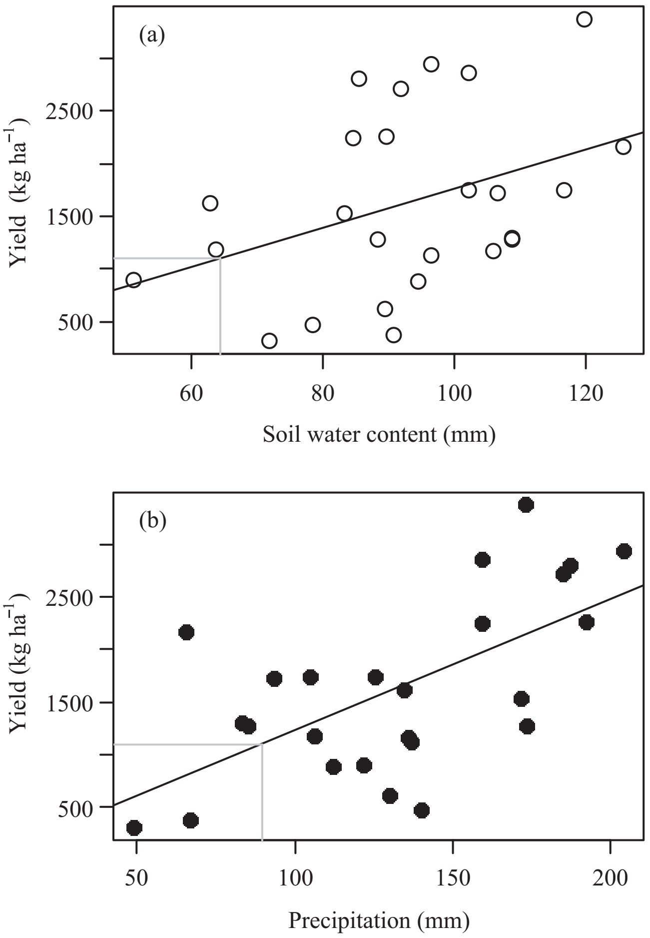

Fig. 3. Relationships between spring wheat yield and water supply factors. Horizontal gray line is the spring wheat yield at 1100 kg ha^{-1}. Yield above this threshold could be classified as normal or otherwise drought.

x (temperature, precipitation), and two categories included in this study were x_i (normal) and x_j (drought). For a solution w^T, it must have the following relations:

$$\begin{cases} w^T x > 0, x \in x_i \\ w^T x < 0, x \in x_j \end{cases} \tag{2}$$

If the vector x_j is multiplied by −1, then the relation for two categories is as follows:

$$w^T x > 0 \tag{3}$$

We added an element of 1 into all the yield vectors, e.g., x_i (temperature, precipitation, 1), and assumed a unit vector, w_0 (1,1,1), for beginning of the calculation w^T. To obtain the condition in Eq. 3 for all yield vectors, we recalculated w^T as follows until we obtained a right solution:

$$w_{k+1}^T = w_k^T + x_k \tag{4}$$

In Eq. 4, x_k is yield category. The initial value of k is zero, and the elements of final w^T are the coefficients of Eq. 1. We used Visual Basic Application in Microsoft Excel 2003 to complete the calculation process above.

3. Results

3.1 Statistical models for determining agricultural drought

3.1.1 Using single factor

Spring wheat yield from FE widely varied from 310 to 3373.7 kg ha^{-1} as soil water content at sowing day ranged from 51 to 126 mm in 50 cm depth of soil profile (Fig. 3a). Although a significant liner relationship existed between the spring wheat yield and soil water content at sowing day, the soil water content could not explain the much higher variation of yield, and there was still 88.4% spring wheat yield variation that could not be explained by soil water content at sowing day (Table 3, Eq. 1). Using Eq. 1, we obtained that agricultural drought would occur when soil water content at sowing day was < 68.8 mm. However, we found that agricultural drought would still occur as soil water content at sowing day was > 68.8 mm (Fig. 3a). Additionally, the yield, 1620 kg ha^{-1}, was classified as normal, with extremely small amount of soil water content at sowing day, only 63 mm.

Similarly, from 1987 to 2011, precipitation during spring wheat growing season widely ranged from 48.9 to 204.2 mm (Fig. 3b). Based on the response of yield to precipitation in Eq. 2 (Table 3), we found that agricultural drought would occur if the precipitation was < 84.3 mm. However, precipitation only explained 27.4% variation of yield, even though the liner relationship between precipitation and yield was at 0.01 significance levels. There is still 72.6% variation of yield that could not be explained by precipitation. Furthermore, agricultural drought frequently occurred as the precipitation was greater than the threshold, i.e., 84.3 mm (Fig. 3b).

3.1.2 Using multiple factors

Precipitation during growing season and soil water content at sowing day are two water supply sources for spring wheat growth; hence, we should consider both factors to determine agricultural drought. As we simultaneously regressed spring wheat yield against precipitation during growing season and soil water content at sowing day while taking into account their interaction and sum, respectively, we obtained three equations (Eqs. 3−5 in Table 3) at 0.01, 0.1, and 0.001 significance levels, respectively. Simultaneous consideration of precipitation and soil water content explained 51.4% variation of yield, but we could not quantificationally determine agricultural drought because of the complementary relationship between one water supply resources to the other for wheat water use. When taking the interaction of the precipitation and water content at sowing day into account, the relationship between both factors and yield was not significant. It might be the reason for no clear effect of one factor on the relation between the yield and another factor. However, when we summed the soil water content in 50 cm soil depth at sowing day and precipitation during spring wheat growing season, it explained 45.6 variation of yield. Additionally, we could determine that there would be no agricultural drought occurrence when the sum of soil water content and precipitation is > 185.9 mm.

Furthermore, high air temperature is an important limited factor coupling with water stress resulting in yield loss in arid and semi-arid areas. Therefore, we took both air temperature and precipitation, two climatic factors, into account to determine

Table 3. Statistical models under different conditions based on different factors.

Type	Variables	Condition	Equation	Number	R^2	Threshold for agricultural drought occurrence (mm)
Single	*swc*	/	$Y=18.6swc-97.8$	1	0.116*	64.4
	p	/	$Y=12.5p-23.3$	2	0.289**	89.7
Multiple	*swc+p*	/	$Y=11.4p+23.3swc-2064.5$	3	<u>0.514**</u>	/
	swc+p+s *swc*: *p*	/	$Y=8.4p+19.7swc+0.03swc{:}p-1724$	4	0.514	/
	(*swc+p*)	/	$Y=12.8\ (p+swc)-1283.8$	5	0.456***	185.9
	p+t	/	/		/	/
Conditional	*swc*	*E-p*<425	$Y=33.5swc-701.9$	6	<u>0.651**</u>	53.8
	swc	*E-p*>=425	$Y=33.4swc-2183.9$	7	<u>0.783***</u>	98.4
	p	*swc*>=98.4	$Y=13.1p+441.1$	8	0.324	50.3
	p	*swc*<98.4	$Y=16.8p-930.4$	9	<u>0.679***</u>	120.7
	p+t	*swc*<98.4	$-28.2t+p+152.5=0$	10	/	$-28.2t+p+152.5<0$

Note: *swc* indicates soil water content at sowing day in 50 cm soil depth. *p* indicates precipitation during spring wheat growing season (March–June). *t* indicates average air temperature during spring wheat growing season (March–June). *E* indicates pan evaporation during spring wheat growing season (March–June). Underlined value indicates $R^2 > 0.5$ with significant probability level of <0.05.
*Significant at 0.05 probability level
**Significant at 0.01 probability level
***Significant at 0.001 probability level
"/" indicates no data. ":" indicates interaction of two factors. "( )" indicates sum of two factors. "+" indicates simultaneously taking different variables into account.

agricultural drought occurrence. As shown in Fig. 4, for drought category, precipitation ranged from 48.9 to 139.9 mm, and most data were below or near the average precipitation, i.e., 133.5 mm. Meanwhile, air temperature varied from 9.6 to 11.6 ℃ for drought category. For normal category, air temperature ranged from 9.1 to 12.4 ℃, and precipitation varied from 65.2 to 204.2 mm. The data of normal category almost displayed at every range of air temperature and precipitation. The result indicated no obvious regulation of display for two different yield categories, except that drought almost occurred under lower amount of precipitation condition. Therefore, we could not find an equation to discriminate agricultural drought from normal category under such situation.

3.1.3 Using conditional factors

Environmental factors might affect each other in some situations. Hence, we analyzed relations between environmental factors and spring wheat yield concerning the effects of other factors on yield. As the soil water content and spring wheat data were presented by growing moisture condition, whether the difference between pan evaporation and precipitation during spring wheat growing season was >425 mm, two distinctly different liner relationships appeared to exist (Fig. 5a, Eqs 6 and 7 in Table 3). Under wet air condition, soil water content at sowing day could explain 65.1% variation in yield, and there would be no agricultural drought occurrence as soil water content was >53.8 mm. Meanwhile, 78.3% variation of yield could be explained by soil water content at sowing day under dry air condition, and the threshold of soil water content at

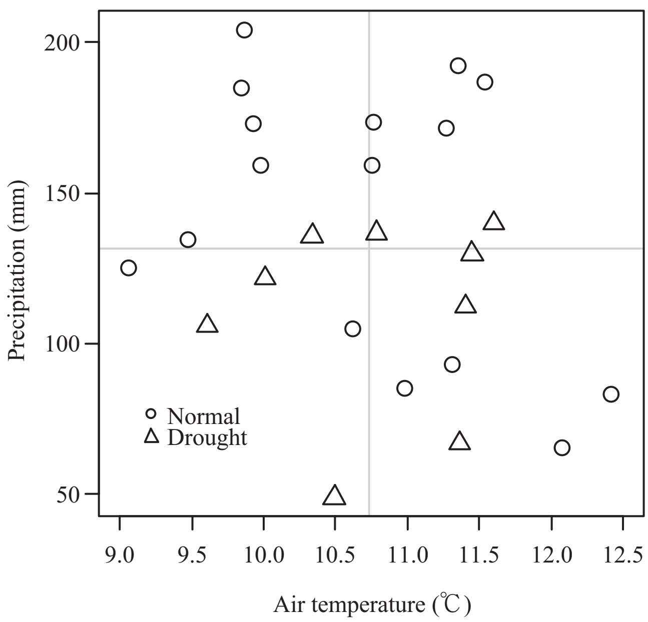

Fig. 4. Display of yield class by air temperature and precipitation ranged from March to June during 1987–2011. The categories of final spring wheat yield, normal and drought, are classified by a threshold of 1100 kg ha^{-1}. Vertical and horizontal gray lines are average air temperature and precipitation during spring wheat growing season from 1987 to 2011, 10.7 ℃ and 133.5 mm, respectively.

sowing day for agricultural drought occurrence was 98.4 mm. If we find soil water content at sowing day of >98.4 mm, we suggest there certainly would be no agricultural drought occurrence, and the value is completely different from that obtained from Eq. 1.

When we regressed precipitation against spring wheat yield while taking soil water content at sowing day into account, we found there were two different responses of yield to precipitation (Fig. 5b, Eqs. 8 and 9 in Table 3), which were clearly defined by the soil water at sowing day of >98.4 mm and <98.4 mm. For soil water content at sowing day of <98.4 mm, the yield ranged from 300 to 2950 kg ha^{-1}, whereas the precipitation varied from 50 to 210 mm. However, for soil water at sowing day of >98.4 mm, the yield ranged from 1100 to 3373.7 kg ha^{-1}, and precipitation increased from 65.2 to 173 mm. Although the agricultural drought threshold is 50.3 mm in Eq. 8, it is easy to obtain an amount of precipitation during spring wheat growing season of >50.3 mm in Dingxi (probability >99% from statistical calculation during 1971–2011, from an unpublished manuscript). Therefore, it might indicate that as soil water at sowing day was >98.4 mm, there would be no drought occurrence in Dingxi. The conclusion is the same as for the result obtained from the relationship between soil water content at sowing day and spring wheat yield above. Meanwhile, under dry soil water condition at sowing day, the threshold of agricultural drought occurrence for precipitation was 120.7 mm.

Furthermore, when the data in soil water content at sowing day of >98.4 mm were eliminated, apparently there were two yield categories existing (Fig. 6). Normal category displayed at the region where precipitation was greater than average precipitation with a lower average air temperature. However, drought category was displayed at the opposite position. Using pattern recognition, a line was found to apparently demarcate the two classes of yield in Fig. 6. The liner equation is shown in Eq. 10 (Table 3).

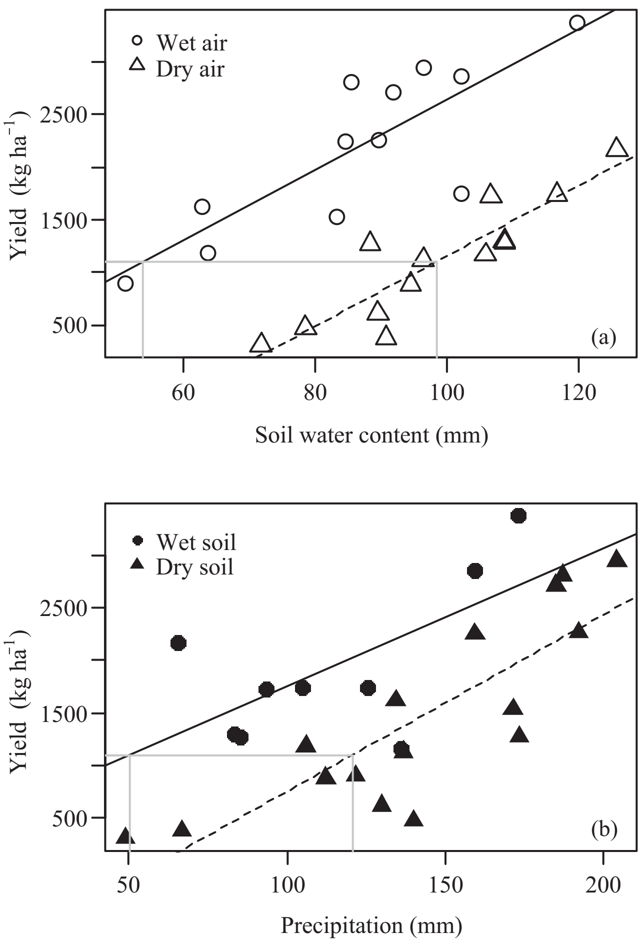

Fig. 5. Response of spring wheat yield to water supply factors while taking other factors into account. Horizontal gray line is the spring wheat yield at 1100 kg ha^{-1}. Yield above this threshold could be classified as normal or otherwise drought. Air is the growing season moisture condition divided by two categories, dry and wet, based on whether the difference between pan evaporation and precipitation during spring wheat growing season is >425 mm. Soil is the soil water condition at sowing day classified by two categories, dry and wet, based on whether soil water at sowing day is >98.4 mm or <98.4 mm.

3.2 Evaluation and application of the statistical models

3.2.1 Evaluation of the statistical models based on meteorological data

The soil water content in 50 cm depth at sowing day was significantly related to sum of precipitation during previous 7 months (August–February) (Fig. 7). The amount of precipitation from August to February could explain 39.9% variation of soil water content in 50 cm depth at sowing day. It

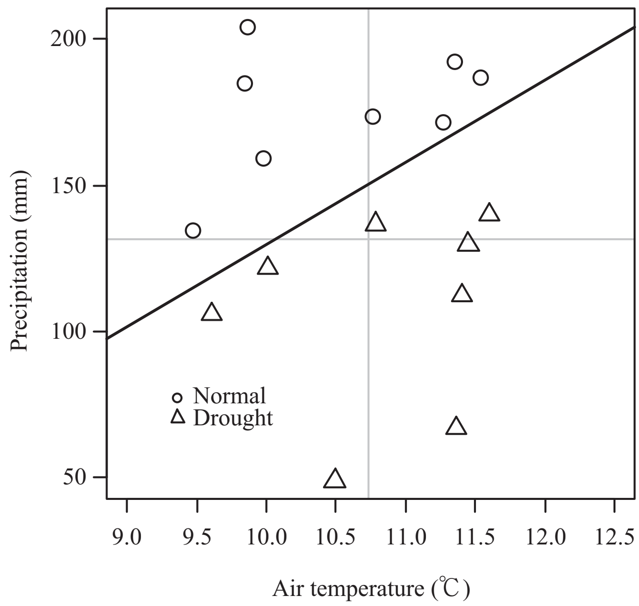

Fig. 6. Display of yield class by air temperature and precipitation ranged from March to June during 1987–2011 when soil water content at sowing day was <98.4 mm. The categories of final spring wheat yield, normal and drought, are classified by a threshold of 1100 kg ha^{-1}. Vertical and horizontal gray lines are average air temperature and precipitation during spring wheat growing season from 1987 to 2011, 10.7 ℃ and 133.5 mm, respectively.

could also explain 66.9% variation of soil water content at sowing day if the data in 1988, 1989, 1992, 1995, and 2007, which apparently were below the regression line, were removed.

We used the relations between observational soil water at sowing day and the amount of precipitation during previous 7 months before sowing to determine the soil water from 1980 to 2013 at sowing day each year. Meanwhile, based on Eqs. 6−10, the obtained data of soil water content at sowing day were combined with the precipitation, temperature, and difference of pan evaporation and precipitation during wheat growing season in each year to determine the occurrence of agricultural drought. Additionally, the observational categories for drought and normal were defined by data of DBS during 1980−2013 (Fig. 8) to confirm the statistical models accuracy and validity. From categories represented by the data of DBS, we found that agricultural drought frequently occurred in the study area, up to 12 times in 34 years, i.e., more than one-third. However, using precipitation under vary soil water content at sowing day, Eqs. 8 and 9, it determined the normal yield in 25 times (only nine times for agricultural drought occurrence), and the accuracy was approximately 71.9%. Similarly, the accuracy for identification of agricultural drought using pattern recognition, Eq. 10, was approximately 70.6%. Nevertheless, based on Eqs. 6 and 7, the estimated soil water content at sowing day determined the agricultural drought occurrence was more accurate, up to 76.5%.

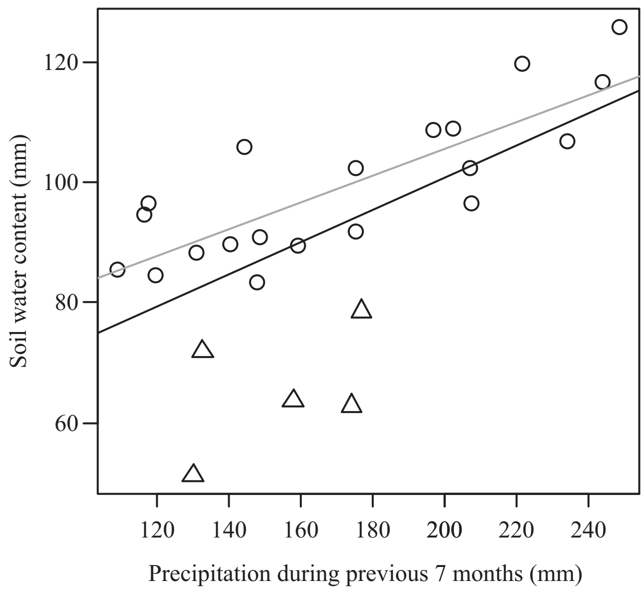

Fig. 7. Soil water content at sowing day as affected by precipitation during previous 7 months (August−October and December−February). Black line included all data from 1987 to 2011: $swc = 0.27722pp7 + 46.751$ ($R^2 = 0.399$, $P < 0.001$); gray line removed the data of 1988, 1989, 1992, 1995, and 2007 (triangle): $swc = 0.2213pp7 + 61.309$ ($R^2 = 0.669$, $P < 0.001$) (*pp7* indicates precipitation during previous seven months).

3.2.2 Probability of agricultural drought occurrence

Using the long-term records of precipitation and pan evaporation from 1960 to 2013, we constructed probability distributions of difference between pan evaporation and precipitation during spring wheat growing season and soil water content at sowing day. The probability of obtaining at most 70 mm soil water content at sowing day nearly approached zero (Fig. 9). We conclude that there would be no agricultural drought occurrence under wet air condition during growing season (soil water content < 53.8 mm, Eq. 6 in Table 3). Therefore, we only focused on the agricultural drought occurring under dry air condition during growing season. Occurrence of dry soil water status (soil water content at sowing day, <98.4 mm) would be 56.4%, and the dry air condition during growing season

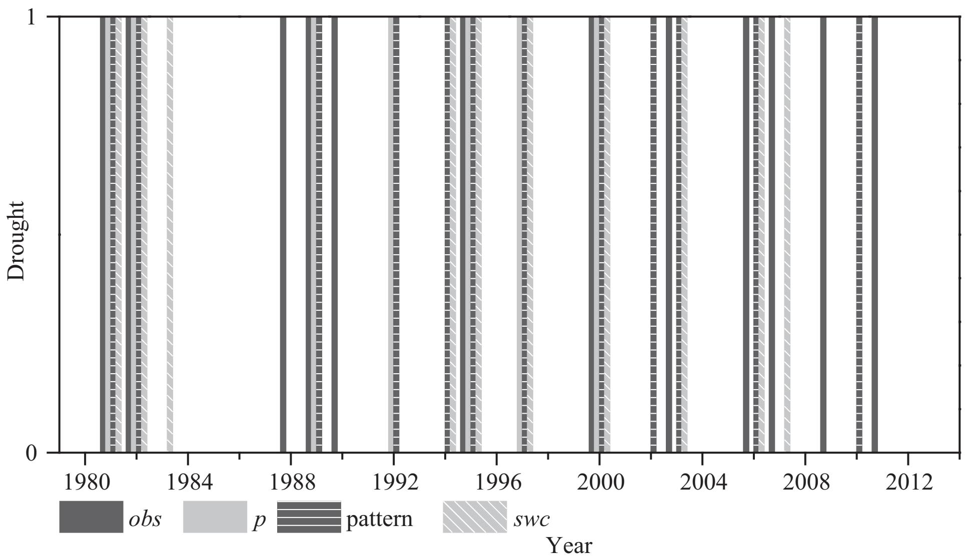

Fig. 8. Comparison between observation and prediction of three different statistical models for agricultural drought occurrence during 1980−2013. The value of vertical coordinates at "0" indicates no drought occurrence, whereas "1" indicates drought occurring. *obs* indicates observational data based on statistical data; *p* indicates using precipitation based on Eqs. 8 and 9 in Table 3; pattern indicates using pattern recognition based on Eq. 10 in Table 3; *swc* indicates using soil water content at sowing day based on Eq. 7 in Table 3.

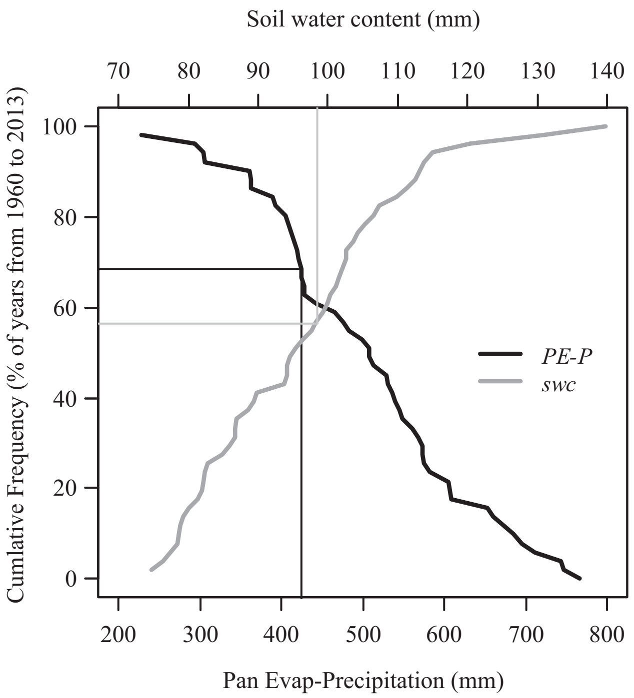

Fig. 9. Probability of obtaining < 98.4 mm soil water content at sowing day and at least 425 mm difference of pan evaporation and precipitation during spring wheat growing season from 1960 to 2013. *PE-P* indicates the difference between pan evaporation and precipitation during spring wheat growing season; *swc* indicates soil water content at sowing day.

(*PE-P* > 425 mm) would occur at 68.5% (Fig. 9). Based on Eq. 7, agricultural drought for spring wheat would occur at 38.6% in the studies area. The probability is nearly similar to the frequency of observational agricultural drought occurrence during 1980−2013, i.e., 12 times in 34 years (35.2%) (Fig. 8).

4. Discussion

Although water is the main limiting factor for crop yield in semi-arid areas, we were unable to accurately determine agricultural drought based on single water supply factor without taking other environmental factors into account. In this study, when spring wheat yields were regressed against single water supply factor, precipitation during spring wheat growing season and soil water content in 50 cm depth, respectively, we found that the single factor could only explain as high as 30% variation of yield. However, in some studies, precipitation during growing season had significant relationship with crop yield (Parthasarathy *et al*., 1988; Sneva, 1982), and drought indices based on precipitation and other climatic factors during the crop growing period could precisely monitor agricultural drought (Kattelus *et al*., 2016; Potopová *et al*., 2016; Yamoah *et al*., 2000). The cause of the different results is that some crops have longer growing season, whereas others have shorter growing season. Spring wheat is a typical short growing season crop and greater soil water storage before sowing would result in a higher biomass during vegetative period even in a year lacking precipitation during growing season. Thus, as spring wheat then obtains even a small amount of precipitation in reproductive stage, it could receive a specific amount of yield, which may be easily greater than the yield threshold (1100 kg ha^{-1}) for agricultural drought occurrence in this study. Therefore, as the soil water content at sowing day was not taken into account, using only climatic factors, precipitation, and temperature during spring wheat growing season, we could not classify the different categories of yield, normal and drought. This may be the reason why Kumar *et al*. (1998) could not find a liner equation for determining agricultural drought in their study. Furthermore, Lyon *et al*. (1995) found a response of crop yield variability explained by soil water content at sowing day to duration of crop growing days. Using this relationship, 50% variation in yield would be explained by soil water at sowing day with average 120 days of growing season for spring wheat, whereas only 11.6% variation of yield was explained by soil water in the current research. The spring wheat root could reach a depth of 1.1 m (Thorup *et al*., 2009). The soil water content in this study was at a soil depth of 50 cm, a very limited value compared with 121.9 cm depth in the study by Lyon *et al*. (1995). Therefore, with such a single limited data, it is not a good choice to determine agricultural drought only depending on soil water at sowing day without taking other environmental factors into account.

Different water supply sources and climatic factors greatly affect the relation between environmental factors and crop yields. When we combined the two water supply factors, i.e., soil water content at sowing day and precipitation during growing season, and summarized them, the explained yield variation grew to 50% (Eqs. 3 and 5 in Table 3). However, as we conditionally correlated one of them with spring wheat yield, we found the explained variation of yield to be greater than 55%, and even up to 80% (Eqs. 6, 7 and 9). It indicates that if one water supply source was eliminated, the other one would be the main factor to determine agricultural drought and the final yield for spring wheat. Meanwhile, as soil water content at sowing day increased to greater than 98.4 mm, the response of yield to precipitation decreased. It indicates that per increased precipitation might produce more amount of yield under dry soil condition than wet soil condition at sowing day to increase the precipitation usage efficiency. Moreover, because of a higher slope at dry soil condition and lower slope at wet soil condition, with increased precipitation, the two liner relationships could obtain the same yield at a great precipitation (Fig. 5b). It indicates that as precipitation increases at a specific amount for enough water supply of crop use, the influence of soil water content at sowing day on crop yield could be neglected. Nielsen *et al*. (2009) obtained the same result, although he used the precipitation in critical period of maize, compared with the precipitation during whole growing season in this study.

Interestingly, Nielsen *et al*. (2002) found there was great influence of air moisture condition on the relationship between available soil water at sowing day and yield of winter wheat, a long season crop. Further, wet air condition resulted in a greater slope of yield response to soil available water. Under wet air condition, with greater amount of water supply and smaller evaporative demand, the crop grows faster than under dry air condition in arid and semi-arid climates, and it would lead to collection of more production with per millimeter increased soil water at sowing day. However, in this study, the slopes of two responses of yield to soil water content at sowing day were almost equal to each other, 33.4 and 33.5 kg ha^{-1} mm^{-1}, respectively. The reason is that with a very limited soil depth profile, 50 cm in this study versus 180 cm in the study by Nielsen *et al*. (2002), spring wheat would exhaust the soil water rapidly, irrespective of whether wheat above ground biomass is great or not. Therefore, even under wet air condition during growing season, spring wheat could not make more efficient water use of stored water in 50 cm depth of soil profile compared with the years under dry air condition.

High air temperature coupling with water stress could result in great yield loss in arid and semi-arid climates. In our research work, we found that use of the two factors, air temperature and precipitation, could demarcate yield class for drought prediction under dry soil condition before sowing, and agricultural drought always occurred under conditions with low precipitation and high air temperature (right lower quadrant in Fig. 6). Meanwhile, with same growing season precipitation, agricultural drought tended to occur under higher air temperature (Fig. 6). High air temperature has great impact on photosynthesis as crop grows under water-limited condition (Perdomo *et al*., 2016). Therefore, it could affect crop biomass accumulation and final crop yield. It suggests that we should take influence of high air temperature on yield into account as we model or deal with agricultural drought.

The threshold of agricultural drought occurrence adopted in this study is the reduction of yield up to 25% compared with long-term averaged spring wheat yield in the research area. This kind of approach is commonly used in agricultural drought research in many areas, but it is still a bit arbitrary for agricultural drought identification due to lacking physiological mechanism for crop water deficit. Meanwhile, because of climate change, variation of crop variety and different climatic types in vary areas, the long-term mean yield might be totally different from one region to another or fluctuate greatly during different research periods, e.g., 1964–1979 and 1980–2013 in this study. Therefore, it may be very difficult to compare the identification of agricultural drought from one region with another or the same area during different periods. However, it still lacks a commonly accepted standard to assess agricultural drought and quantify agricultural drought degree worldwide to date. Because of special features of agricultural drought, taking soil, plant, and atmosphere together into account (Woli, 2010) and using crop model as a verified tool to find a common approach to quantify agricultural drought are essential for risk assessment for crop production under increasingly severe water crisis of the world.

Drought indices have been commonly used to estimate the effect of drought on crop yield loss, such as Standardized Precipitation Index, Palmer Drought Severity Index (Mavromatis, 2010) and Standardized Precipitation Evapotranspiration Index (Potopová *et al*., 2016). However, these types of indices always neglect the great impact of soil water content at sowing on final yield, especially for crops with short growing season, e.g., spring wheat in this study. Therefore, the drought indices might overestimate the drought severity only based on climatic factors during crop growing season. Even though some researchers used drought indices based on climatic factors during several months before sowing to estimate the influence of soil water storage on crop yield (Yamoah *et al*., 1998; Wang *et al*., 2018), they could not distinguish the different impact of water resource on crop final yield under different growing conditions. In fact, most indices used at present around the world are climatological drought indices, and they still have some problems of predicting yield and risk assessment for specific crop in a certain location. In the current study, we found that the soil water condition before sowing interacted with the growing season moisture condition and resulted in variable spring wheat yield. It makes the assessment for effect of agricultural drought on yield much more complex. Hence, using these climatological drought indices in a specific area, we suggest it would pay much more attention to agricultural drought occurrence under different environmental conditions.

5. Conclusion

Quantificationally determining agricultural drought is very difficult based on several limited environmental factors. However, as we used one or two water supply factors while taking other factors into account, we certainly determined agricultural drought, and the methods in this study can be used to determine agricultural drought for spring wheat. Using the statistical models in this study and long-term records of precipitation and pan evaporation, we confirm the highly risky nature of agricultural drought occurrence for spring wheat in the semi-arid area. With close relationship between soil water content at sowing day and spring wheat yield under different growing season conditions, we recommend that the farmers in this area should make every effort to increase soil water storage before sowing to deal with the potential spring wheat yield loss risk caused by agricultural drought.

Acknowledge

The authors sincerely thank the anonymous reviewers for their valuable comments and suggestions for improving the quality of this manuscript. The authors also gratefully acknowledge the help of Doctor Quanxiao Fang for his comments on the first draft of this paper. This research was jointly supported by National Natural Science Foundation of China (41375019), China Special Fund for Meteorological Research in the Public Interest (Major projects) (GYHY201506001-2), Natural Science Foundation of Gansu Province (145RJYA284), and Meteorological Research Program of Gansu Provincial Meteorological Service (GSMAMs2018-14).

Reference

Boken VK, Haque CE, Hoogenboom G, 2007: Predicting Drought Using Pattern Recognition. *Annals of Arid Zone* **46**, 133–144.

Gouache D, Bouchon AS, Jouanneau E, Bris XL, 2015: Agrometeorological analysis and prediction of wheat yield at the departmental level in France. *Agricultural & Forest Meteorology* **209**, 1–10.

Huang M, Gallichand J, Zhong L, 2004: Water-yield relationships and optimal water management for winter wheat in the Loess Plateau of China. *Irrigation Science* **23**, 47–54.

Huang Y, Chen L, Fu B, Huang Z, Gong J, 2005: The wheat yields and water-use efficiency in the Loess Plateau: straw mulch and irrigation effects. *Agricultural Water Management* **72**, 209–222.

Kattelus M, Salmivaara A, Mellin I, Varis O, Kummu M, 2016: An evaluation of the Standardized Precipitation Index for assessing inter-annual rice yield variability in the Ganges-Brahmaputra-Meghna region. *International Journal of Climatology* **36**, 2210–2222.

Kumar V, Panu U, 1997: Predictive assessment of severity of severity of agricultural droughts based on agro-climatic factors. *Journal of the American Water Resources Association* **33**, 1255–1264.

Kumar VB, Haque CE, Pawlak M, 1998: Determining agriculturaldrought using pattern recognition. In *PrairiePerspectives-Geographical Essays*. Department of Geography, University of Winnipeg, Winnipeg, Manitoba, Canada, pp. 74–80.

Li FM, Wang H, Wang J, Xu JZ, 2004: Effects of irrigation before sowing and plastic film mulching on yield and water uptake of spring wheat in semiarid Loess Plateau of China. *Agricultural Water Management* **67**, 77–88.

Li G, Zhao B, Dong S, Zhang J, Liu P, Vyn TJ, 2017: Impact of controlled release urea on maize yield and nitrogen use efficiency under different water conditions. *Plos One* **12**, e0181774.

Lyon DJ, Boa F, Arkebauer TJ, 1995: Water-yield relations of several spring-planted dryland crops following winter wheat. *Journal of Production Agriculture* **8**, 281.

Mannocchi F, Todisco F, Vergni L, 2004: Agricultural drought: indices, definition and analysis. In *The Basis of Civilization-Water Science*? Rome, pp. 246–254.

Mavromatis T, 2010: Drought index evaluation for assessing future wheat production in Greece. *International Journal of Climatology* **27**, 911–924.

Nielsen DC, 1997: Water use and yield of canola under dryland conditions in the central Great Plains. *Journal of Production Agriculture* **10**, 307–313.

Nielsen DC, Vigil MF, Anderson RL, Bowman RA, Benjamin JG, Halvorson AD, 2002: Cropping System Influence on Planting Water Content and Yield of Winter Wheat. *Agronomy Journal* **94**, 962–967.

Nielsen DC, Vigil MF, Benjamin JG, 2009: The variable response of dryland corn yield to soil water content at planting. *Agricultural Water Management* **96**, 330–336.

Nielsen DC, Lyon DJ, Hergert GW, Higgins RK, Holman JD, 2015: Cover crop biomass production and water use in the Central Great Plains. *Agronomy Journal* **107**, 2047–2058.

Panu US, Sharma TC, 2002: Challenges in drought research: some perspectives and future directions. *Hydrological Sciences Journal* **47**, 19–30.

Parthasarathy B, Munot AA, Kothawale DR, 1988: Regression model for estimation of indian foodgrain production from summer monsoon rainfall. *Agricultural and Forest Meteorology* **42**, 167–182.

Perdomo JA, Carmosilva E, Hermidacarrera C, Flexas J, Galmés J, 2016: Acclimation of biochemical and diffusive components of photosynthesis in rice, wheat, and maize to heat and water deficit: implications for modeling photosynthesis. *Frontiers in Plant Science* **7**, 1–16.

Ponce CGE, Moran MS, Huete A, Zhang Y, Bresloff C, Huxman TE, Eamus D, Bosch DD, Buda AR, Gunter SA, Scalley TH, Kitchen SG, Mcclaran MP, Mcnab WH, Montoya DS, Morgan JA, Peters DPC, Sadler EJ, Seyfried MS, Starks PJ, 2013: Ecosystem resilience despite large-scale altered hydroclimatic conditions. *Nature* **494**, 349–352.

Potopová V, Boroneanţ C, Boincean B, Soukup J, 2016: Impact of agricultural drought on main crop yields in the Republic of Moldova. *International Journal of Climatology* **36**, 2063–2082.

Qin S, Li L, Wang D, Zhang J, Pu Y, 2013: Effects of limited supplemental irrigation with catchment rainfall on rain-fed potato in semi-arid areas on the western Loess Plateau, China. *American Journal of Potato Research* **90**, 33–42.

R Development Core Team, 2014: *R: a language and Environment for Statistical Computing*, Vienna, Austria.

Schillinger WF, Schofstoll SE, Alldredge JR, 2008: Available water and wheat grain yield relations in a Mediterranean climate. *Field Crops Research* **109**, 45–49.

Sneva FA, 1982: Relation of precipitation and temperature with yield of herbaceous plants in eastern Oregon. *International Journal of Biometeorology* **26**, 263–276.

Stone LR, Schlegel AJ, 2006: Yield-water supply relationships of grain sorghum and winter wheat. *Agronomy Journal* **98**, 1359–1366.

Thorup KK, Cortasa MS, Loges R, 2009: Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses? *Plant and Soil* **322**, 101–114.

Wang SS, Mo XG, Hu S, Liu SX, Liu ZJ, 2018: Assessment of droughts and wheat yield loss on the North China Plain with an aggregate drought index (ADI) approach. *Ecological Indicators* **87**, 107–116.

Wilhite DA, 1993: *Drought Assessment*, *Management*, *and Planning: Theory and Case Studies*, Kluwer Academic Publishers, New York.

Woli P, 2010: *Quantifying water deficit and its effect on crop yields using a simple*, *generic drought index*. Dissertations and Theses, University of Florida.

Wu J, He B, Lü AL, Zhang ML, Lin Z, 2011: Quantitative assessment and spatial characteristics analysis of agricultural drought vulnerability in China. *Natural Hazards* **56**, 785–801.

Yamoah CF, Varvel GE, Francis CA, Waltman WJ, 1998: Weather and management impact on crop yield variability in rotations. *Journal of Production Agriculture* **11**, 219–225.

Yamoah CF, Walters DT, Shapiro CA, Francis CA, Hayes MJ, 2000: Standardized precipitation index and nitrogen rate effects on crop yields and risk distribution in maize. *Agriculture Ecosystems and Environment* **80**, 113–120.

Yu Q, Li L, Luo Q, Eamus D, Xu S, Chen C, Wang E, Liu J, Nielsen DC, 2014: Year patterns of climate impact on wheat yields. *International Journal of Climatology* **34**, 518–528.

Zhang GS, Chan KY, Li GD, Huang GB, 2008: Effect of straw and plastic film management under contrasting tillage practices on the physical properties of an erodible loess soil. *Soil and Tillage Research* **98**, 113–119.