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RESEARCH ARTICLE

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Predicting spring wheat yields based on water use-yield production function in a semi-arid climate

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Abstract

Grain yield of spring wheat (*Triticum aestivum* L.) fluctuates greatly in Western Loess Plateau of China due to limited and highly variable precipitation. Farmers in this area need a simple tool to predict spring wheat grain yield and assess yield loss risk efficiently. The objectives of this study were to establish relations between water use and grain yield of spring wheat for predicting actual yield and attainable yield (water limited yield) under conventional management practice and mulching practices. Reference data during 1993-2013 and field experiment conducted from 1987 to 2011 were used to determine water use-yield production function and boundary function for spring wheat. Probability of achieving a given spring wheat grain yield threshold is determined based on available soil water content at sowing plus expected precipitation during growing season. Single linear equation was obtained with slope of 14.6 kg ha^{-1} mm^{-1} and x intercept at 126.3 mm for spring wheat water use-yield production function with different wheat varieties under varying climatic patterns. The slopes of the boundary function were 16.2 kg ha^{-1} mm^{-1} and 19.1 kg ha^{-1} mm^{-1} under conventional management practice and mulching practices, respectively. With increase of available soil water content at sowing, the probability of achieving at least 2000 and 4000 kg ha^{-1} of spring wheat for actual and attainable yield increased under different agricultural management practices.

Additional keywords: soil water; precipitation; attainable yield; agricultural management; mulching.

Abbreviations used: ADC (atmospheric dryness condition); ASWC (available soil water content); AWS (available water supply); CWUPF (crop water use-yield production function); LWA (lower limit of water availability); SWC (soil water content); WLP (Western Loess Plateau).

Authors' contributions: Conceived and designed the experiments: FZ, RW and QY. Performed the experiments: JL, KZ and FZ. Analyzed the data: FZ, KZ and QY. Wrote the paper: FN and QY. All authors read and approved the final manuscript.

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Introduction

Semi-arid climate is characterized by cold winter, warm summer, small amount but highly erratic precipitation. Although high temperature also could result in great crop yield loss, production of crop in areas under this climate is heavily dependant on limited water. However, with global climate warming, water shortage becomes much more severe, especially in arid and semi-arid climate (Dai, 2013). It highlights the need of establishing several tools in these areas to predict crop final yield and assess agricultural production risk and adopting suitable agricultural management practice to improve crop yield efficiently.

Under water limited condition, researchers found crop yield has linear relation with water use (Kirkham, 2005), which is commonly defined as crop water use-yield production function (CWUPF) (Varzi, 2016). It is very useful for crop yield prediction and production risk assessment. However, some researchers stated that the CWUPF is species and site specific (Faci & Fereres, 1980; Nielsen *et al.*, 2011). It indicates that the species and geographic transferability of CWUPF is questionable. For example, Nielsen *et al.* (2011) reported that the slope and x intercept of CWUPF was totally different with each other for ten different crops in Central Great Plains. Meanwhile, Nielsen & Vigil (2017a) reviewed the CWUPF for sorghum worldwide, and they found the slope and x intercept of those relations changed greatly in different areas. For wheat, Moberly *et al.* (2017) showed that the slopes of relationship between water use and wheat yield varied from 3.08 to 19.6 in semi-arid regions of the High Plains, and x intercept also had wide variation, from -118 to 218 mm. Zhang & Oweis (1999) reported slopes of CWUPF at 11.6 and 16.0 kg ha^{-1} mm^{-1} for two different types of wheat in a Mediterranean-type environment at northern Syria. Huang *et al.* (2004) reported a slope of 11.2 kg ha^{-1} mm^{-1} for winter wheat in Loess Plateau of China with a semi-arid climate. However, Kang *et al.* (2002) and Wang *et al.* (2011) found slope of 13.4 and 15 kg ha^{-1} mm^{-1} for winter wheat in the same area, respectively. From those reports, it seems that it would be difficult to use a single CWUPF obtained from one research for a specific crop in a given location to predict crop yield and assess production loss risk.

Attainable yield, which is potential yield determined by solar radiation under water or nutrients limited conditions (Yu *et al.*, 2014), plays critical roles in agricultural management in water limited areas. However, estimation of it is very complex. At present, crop model has been commonly used to calculate attainable yield for different crops (Hoffmann *et al.*, 2018), but this tool has large number of parameters to be calibrated before we use it. Fortunately, the approach adopted by French & Schultz (1984) is another way to estimate attainable yield under water limited condition. Based on an extensive set of wheat yield and water use relations, French & Schultz (1984) suggested using a linear boundary function represents attainable yield per unit water use. The x intercept of the linear boundary function was the average soil evaporation and the slope of the line could represent attainable transpiration efficiency. Although with some criticism of not accounting for the time of water stress, assuming constant total soil evaporation and not taking runoff and out of growing precipitation on water budget into account (Angus & Herwaarden, 2001; Whitbread & Hancock, 2008), the approach has been popularly used in some water limited areas (Robertson & Kirkegaard, 2005; Grassini *et al.*, 2009; Patrignani *et al.*, 2014;), even in some semi-humid climate (Hancock, 2007), due to its easy realization with limited data (Sadras & Angus, 2006).

Spring wheat was once the most commonly sowed crop in Western Loess Plateau (WLP) with a typical semi-arid climate (Xie *et al.*, 2005). Recently, farmers in WLP are reluctant to sow spring wheat, due to its great variation of yield under highly variable precipitation with uneven distribution (Huang *et al.*, 2007). However, farmers choose to sow spring wheat in some years for household use (Nolan *et al.*, 2008). Hence, quantifying the probability of achieving an expected spring wheat yield is very helpful for grain supply in this area. Therefore, the objectives of this study were to: (1) establish a CWUPF for spring wheat in WLP; (2) determine the probabilities of achieving two typical spring wheat grain yield thresholds, 2000 and 4000 kg ha^{-1}, under different agricultural managements.

Material and methods

Study area

The studies were carried out at Dingxi (104°12′-105°01′E, 35°17′-36°02′N, 1898.7 m a.s.l. in average), Gansu province of China. The area is located in WLP. Mean annual radiation hour in this area is 2500.1 h and the average annual temperature is about 6.3 °C. The mean annual precipitation is about 386 mm. The soil type is a typical loessial soil. Due to lack of irrigation resource, spring wheat growth in this area mainly depends on precipitation.

Reference data collection

The data in references were collected from published papers found on the Web of Science and the China National Knowledge Infrastructure (CNKI) based on combining keywords ‘spring wheat’, ‘water use’ (or ‘evapotranspiration’) and ‘Dingxi’. Spring wheat yield and water use data were taken directly from table or digitized from graphs with help of the software, GetData Graph Digitizer (http://getdata-graph-digitizer.com). Data in the references with sufficient nutrient level were collected and the data under highest fertilization were also included in studies with both high and low fertilizer level treatments. We divided the collected data into two main groups, one under conventional management practice (without mulching), and the other under mulching practices (including straw and plastic mulching).

Additionally, the data of spring wheat yield and water use with irrigation was distinguished by three types, including no irrigation (NI), irrigation before sowing (IBS) and irrigation during spring wheat growing season (IGS). Forty-eight records were collected in total during 1993-2013 at Dingxi under conventional management practice without mulching, which was used to determine CWUPF. And thirty nine records of water use and yields under mulching practices were collected.

Field experiment

The field experiment was conducted from 1987 to 2011 at the Dingxi agro-meteorological station (35°35′N, 104°36′W, 1898 m a.s.l.), affiliated with Chinese Meteorological Administration (CMA). The experimental cropland had four plots. Individual plot size was 10 by 25 m with north-south row direction. The spring wheat (*Triticum aestivum* L.) was sowed in March and its main growing season was from March to June. The varieties of spring wheat sowed were identical to the varieties used by the local farmers. During 1987-2011, the varieties changed every four or five years, including 'Weichun1', 'Weichun27', 'Longchun81139', 'Longchun35' and 'Dingxixin24'. The maturity types of those varieties were middle and middle late. The seeding density was approximately from 187.5 to 225.0 kg ha^{-1}. The stem and grain yield was measured and averaged at four replicated square meters at harvest and the mean was multiplied 10000 to obtain the stem and yield in one hectare, respectively.

Daily precipitation, temperature and pan evaporation were measured at a weather station approximately 100 m from the plot area. Monthly precipitation, pan evaporation, and average temperature were computed based on daily value. In each year, the amount of precipitation and pan evaporation during spring wheat growing season was the sum of precipitation and pan evaporation in March, April, May and June, respectively (Fig. S1a,c [suppl.]). The temperature during spring wheat growing season was the average temperature in March, April, May and June.

Soil water content was measured at spring wheat sowing day during 1987-2011 in four plots by gravimetric sampling at 10 cm intervals to 150 cm depth. Gravimetric soil water content were converted to volumetric water content by multiplying by the soil bulk density in each layer (average bulk density throughout the soil profile was 1.2 g cm^{-3}). The soil water content (SWC) in this study was total water content at soil profile of 150 cm (Fig S1c [suppl.]). Available soil water content (ASWC) was the difference between SWC and the lower limit of water availability (LWA) at soil profile of 150 cm (the average LWA throughout the soil profile was 0.056 m^3 m^{-3}, determined as the lowest volumetric water value observed during 1987 to 2011 in the study site).

Yield level definition

Attainable yield is the maximum crop yield ever achieved under water-limited or nutrition limited conditions. In the current study, we only focused on water-limited condition; therefore, we collected data without nutritional limitation. Meanwhile, the attainable yield was speculated by the maximum yield ever achieved in the research area for a given water use based on a series of recorded data (Connor *et al.*, 2011; Patrignani *et al.*, 2014). Furthermore, actual yield is generally defined as the crop yield obtained under taking limitations of water, nutrition, pests, diseases and weeds into account (Yu *et al.*, 2014), whereas we defined it here as the yield obtained by CWUPF without nutrition, pests, diseases and weeds limitations.

Estimation of water use for field experiment

Because of lack of observational soil water content data at harvest, we could not calculate water use of spring wheat directly for field experiment. Therefore, an approach was adopted to estimate water use. De Wit (1958) reported dry matter (*DM*) related with transpiration (*T*) under dry, high-radiation climates:

$$\frac{DM}{T} = \frac{k}{\overline{E_0}} \qquad [1]$$

where k is a crop specific parameter, and $\overline{E_0}$ is average daily evaporation from free water, which could indicate evaporative demand. Previous researches suggested that the parameter k is more dependent on climatic conditions and latitudes than on the fertilizer level of soil and water supply conditions (Kirkham, 2005). Therefore, we used the value 125 kg ha^{-1} d^{-1} for wheat cultivated at Great Plains under semi-arid climate (Hanks *et al.*, 1969), located in the same latitude of the current study. Meanwhile, $\overline{E_0}$ could be calculated by daily pan evaporation (E_{pan}) through a pan coefficient of 0.7 (Legrand & Myers, 1973). From linear regression based on data collected from references, we could speculate the amount of average soil evaporation in current research area. Therefore, the water use was the sum of estimated T and average soil evaporation. However, in nine years, estimated water use was greater than available water supply

(AWS, sum of ASWC at sowing and precipitation during spring wheat growing season). Hence, we adjusted those great values as AWS.

Statistical analyses

Linear test between stem (and yield) and year was adopted to evaluate the possibility of crop production improvement through management and breeding effect from 1987 to 2011 for field experiment. However, it showed no confidence was placed on a change of spring wheat production potential (Fig. S1e,f [suppl.]). Hence, we had not to make adjustment in yield for the increasing yield trend that results from genetic improvement in the study area.

Cluster analysis for year pattern

Crop yield in semi-arid climate is mainly determined by water condition, including water supply and atmospheric demand, and the water resource for spring wheat yield is the sum of water storage at sowing and precipitation during wheat growing season. Therefore, we could identify year pattern by SWC at sowing and atmospheric dryness condition (difference of evaporative demand and precipitation, ADC) during wheat growing season. First, we grouped SWC at sowing and ADC into seven clusters by using K-means method of clustering in SPSS 13.0. Second, the difference of average spring wheat yield between each cluster was tested at significance level ($p<0.05$) by using Kolmogorov-Smirnov (K-S) tests. Third, if any one group of yield was not significantly different from another, we aggregated those two groups into one. We repeated this approach until there is significant difference between groups. We classified the climatic pattern for each year during 1987-2011 based on data of field experiment and then identified the climatic pattern of the data collected from references. Therefore, we could get the relationship between water use and yield under different climatic patterns for data from both field experiment and references.

The relationship between water use and spring wheat yield was analyzed by linear regression in order to define a CWUPF. The linear regression was carried out by using R with function ‘lm’ and ‘summary’ (R Development Core Team, 2014). Cumulative exceedance probability graph of ASWC at sowing and yields estimated with the production function and boundary function was created based on long-term soil water content at sowing and precipitation during spring wheat growing season from 1987-2011, respectively.

Results

Establishment and verification of CWUPF

Establishment of CWUPF

With water use varying widely from 130 to 490 mm, the spring wheat yield changed greatly from 330 to 5500 kg ha^{-1} (Fig. 1). Although spring wheat varieties in different years from 1993 to 2013 were not identical, there appeared to be a consistently significant linear relationship between water use and spring wheat yield (see $p<0.01$). The spring wheat yield increased 14.6 kg ha^{-1} per mm of water use and there was no spring wheat yield harvest if water use <126.3 mm. The water use could explain 85.3 % variation of spring wheat yield.

Verification of CWUPF

Transpirations of spring wheat in each year of field experiment were estimated based on Eq. [1] and we used the average soil evaporation obtained in Fig. 1, 126.3 mm, plus the transpiration in each year to estimate the water use. Meanwhile, taking the limited available water supply each year into account, we adjusted the water use by comparing the available water supply and estimated water use each year. As shown in Fig 2, we found that the regression line obtained from our field experiment was nearly identical to the function calculated from data of references. Additionally, there was no statistical difference of slope and x intercept between the two lines. Therefore, we believe there was only one CWUPF existing for spring wheat in the study area.

CWUPF under different climatic types and irrigation treatments

Five different climatic patterns were clearly distinguished based on soil water content at sowing and atmospheric dryness condition (Fig. S2 [suppl.]). The spring wheat yield in each pattern was significantly different from another ($p<0.01$). The five climatic patterns included pattern A with the highest spring wheat yield under the lowest atmospheric dryness condition and middle soil water content at sowing, E with the lowest spring wheat yield under the highest atmospheric dryness condition and the lowest soil water content at sowing, and B, C and D with spring wheat yield lower than A, greater than E.

Although spring wheat yield varied greatly under different climatic patterns (Fig. S2a [suppl.]), we found there was no apparent impact of climatic pattern on CWUPF (Fig. 3). The water use and yields were distributed regularly along the regression line

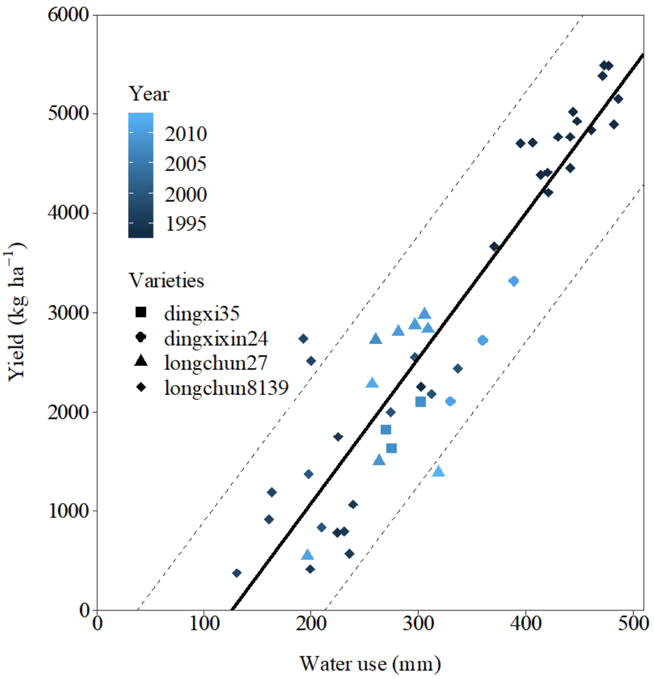

Figure 1. Response of spring wheat yields to water use during 1993-2013 with different wheat varieties and the regression function was Yield [kg ha^{-1}] = 14.626 water use [mm] – 1844.2 (R^2=0.853, p<0.01). The dashed lines on each side of the regression line represent the upper and lower 95 % confidence limits.

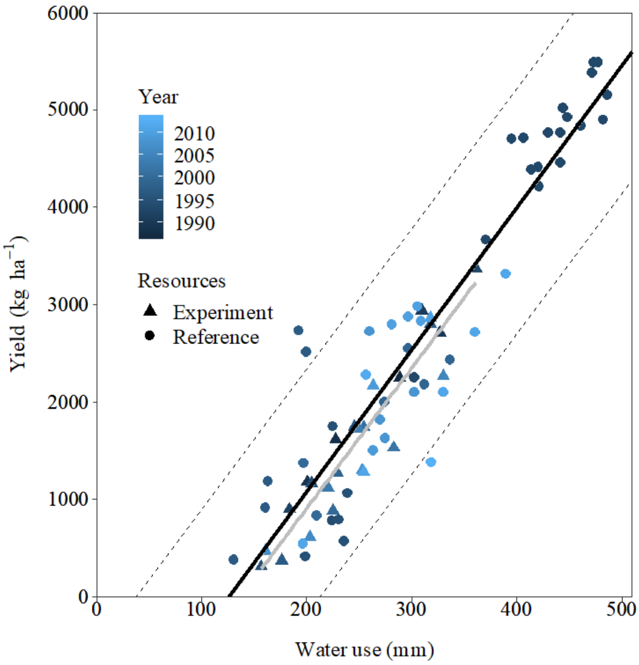

Figure 2. Response of spring wheat yield to water use for field experiment (1987-2011) and references (1993-2013), and the regression function was Yield [kg ha^{-1}] = 14.626 water use [mm] – 1844.2 (R^2=0.853, p<0.01) for data collected from reference (black line) and Yield [kg ha^{-1}] = 14.634 water use [mm] – 1976 (R^2=0.887, p<0.01) for data collected from field experiment (grey line).

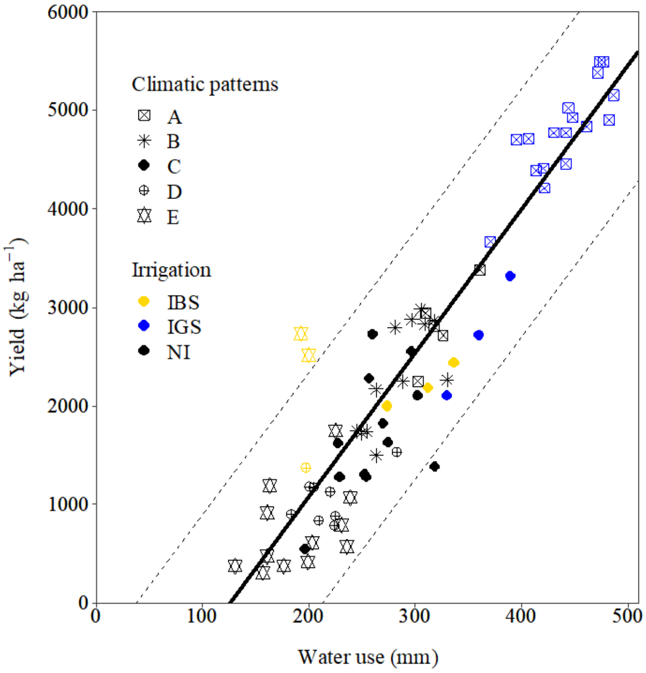

Figure 3. Response of spring wheat yield to water use under different climatic patterns and irrigation conditions, and the regression function was Yield [kg ha^{-1}] = 14.626 water use [mm] – 1844.2 (R^2=0.853, p<0.01). 'A', 'B', 'C', 'D' and 'E' are cluster combination of years of soil water content at sowing and atmospheric dryness condition (see Fig. S2 [suppl.]). IBS= irrigation before sowing. IGS= irrigation during growing season. NI= no irrigation.

under different climatic patterns. In years of pattern E, the spring wheat used the lowest water and obtained the lowest yield due to very limited water supply. However, the highest spring wheat yield was harvested in years under pattern A, due to the medium soil water at sowing and the lowest ADC. The yield and water use relations under pattern B, C and D ranged between A and E along the regression line.

Furthermore, we found that the additional water irrigation had no apparent effect on the CWUPF. With additional water supply in different climatic patterns, the water use increased, but the yield increased still along the regression line. The only exception was the two points under pattern E (Fig. 3). This exception might be the great water supply at sowing resulted in great increase of yield, although there had limited precipitation and the greatest evaporation demand during spring wheat growing season.

Frontier yield production under different management practices

Under mulching practices, the spring wheat yield increased apparently compared with conventional management practice at same water use (Fig. 4). We established two boundary functions for spring wheat under conventional management practice and mulching practices. Under conventional management practice, the potential transpiration efficiency was 16.2 kg ha^{-1} mm^{-1}, whereas 19.1 kg ha^{-1} mm^{-1} for mulching practices. The x-intercept was 104.9 and 95.4 mm for conventional management practice and mulching practices, respectively. Meanwhile, as shown in Fig 4, the irrigation had no apparent effect on the two boundary functions.

Yield risk assessment

Frequency distributions of ASWC

To assess yield risk by CWUPF and boundary functions, we first constructed a cumulative probability exceedance graph for ASWC at sowing by using the data from 1987 to 2011 (Fig. 5). We could deduce the probability of the least amount of stored ASWC at the beginning of spring wheat growing season. From the Fig 5, there is a 95 % chance of having at least 80 mm of ASWC at sowing, whereas 28 % chance of obtaining at least 160 mm of ASWC.

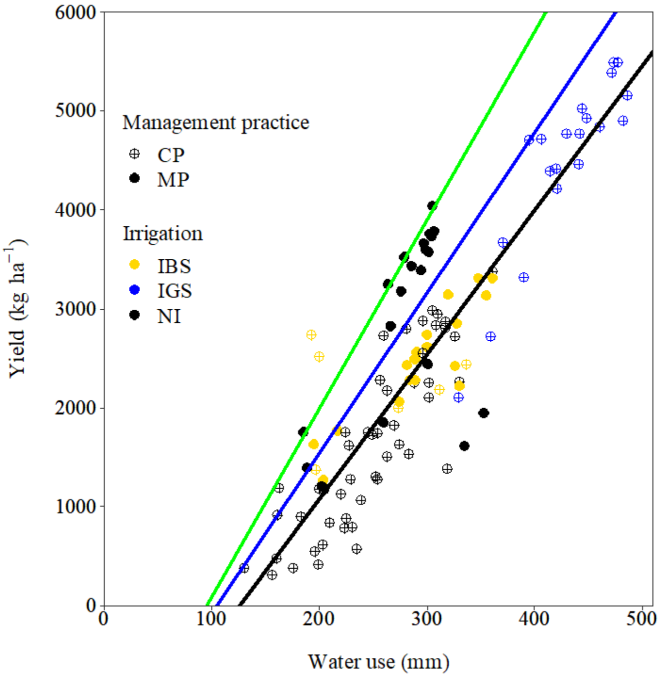

Figure 4. Response of spring wheat yield to water use for field experiment and references under different cropping systems and irrigation conditions, and the CWUPF was Actual Yield [kg ha^{-1}] = 14.626 water use [mm] – 1844.2 (R^2=0.853, p<0.01) (black line), and attainable Yield [kg ha^{-1}] = 16.218 water use [mm] –1700.8 under conventional management practice (blue line) and attainable Yield [kg ha^{-1}] = 19.078 water use [mm] –1820.4 under mulching practices (green line). CP= conventional management practice. MP= mulching practices. IBS= irrigation before sowing. IGS= irrigation during growing season. NI= no irrigation.

Frequency distributions of spring wheat yields

By using the CWUPF and boundary function, we generated cumulative frequency distributions to estimate the probability of obtaining a specific spring wheat yield based on water use estimated as four levels of ASWC at sowing plus precipitation during spring wheat growing season from 1987 to 2011. With ASWC at 80 mm (Fig. 6a), the probability of achieving at least 2000 kg ha^{-1} is only 12.5 % of actual yield and 37.5 % of attainable yield under conventional management practices and 65 % of attainable yield under mulching practices. There is no chance to achieve spring wheat yield greater than 4000 kg ha^{-1} under any treatment with ASWC at 80 mm.

As ASWC increased to 120 mm (Fig. 6b), the probability of achieving spring wheat yield at 2000 kg ha^{-1} is 40 % for actual yield under conventional management practice, 63.5 % and 87.5 % for attainable yield under conventional management practice and mulching practices. The probability of achieving spring wheat at 4000 kg ha^{-1} is about 14 % for attainable yield under mulching practices, whereas there is no chance to achieving 4000 kg ha^{-1} for actual yield and attainable yield under conventional management practice.

The probability of achieving spring wheat yield at least 2000 kg ha^{-1} increased as ASWC increased to 160 mm for two different yield level under different agricultural management practices (Fig. 6c). It is 70, 89 and nearly 100 % for actual yield under conventional management practice and attainable yield under conventional management and mulching practices, respectively. Meanwhile, the probability of achieving 4000 kg ha^{-1} for attainable yield under mulching practices is nearly 50 %, and only 6 % under conventional management practice. The probability of achieving spring wheat yield at least 4000 kg ha^{-1} is still zero for actual yield under conventional management practice.

As ASWC at sowing approaches to 200 mm (Fig. 6d), the two yield levels could reach at least 2000 kg ha^{-1} of spring wheat yield at 100 % probability. However, the probability of achieving at least 4000 kg ha^{-1} for actual yield under conventional management practice is still very low, almost smaller than 2 %. The probability for

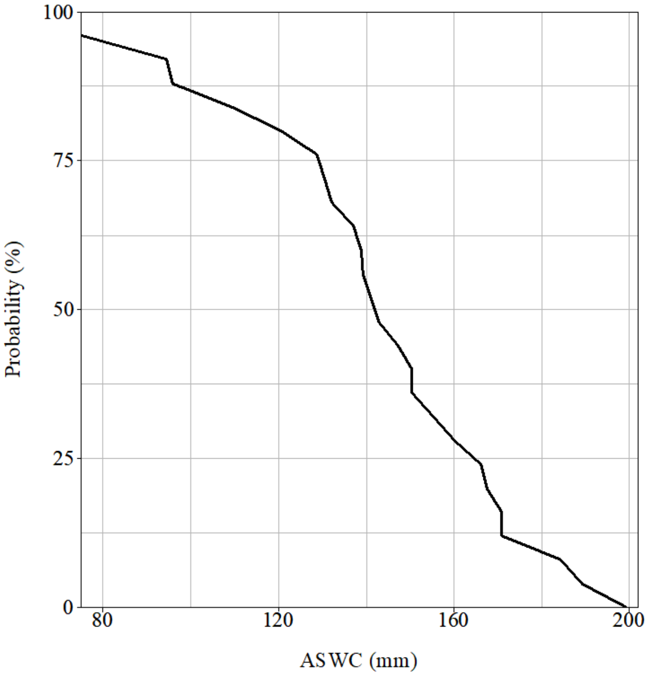

Figure 5. Cumulative exceedance probability for available soil water content (ASWC) at spring wheat sowing day in Western Loess Plateau (WLP).

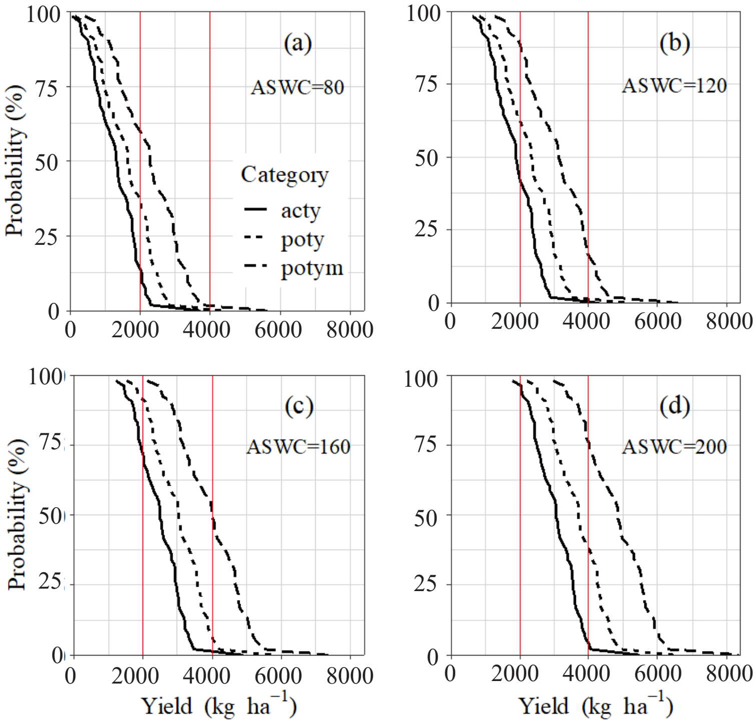

Figure 6. Cumulative exceedance probability for spring wheat yield computed based on the CWUPF Actual Yield [kg ha^{-1}] = 14.626 water use [mm] – 1844.2, Attainable Yield [kg ha^{-1}] = 16.218 water use [mm] – 1700.8 under conventional management practice and Attainable Yield [kg ha^{-1}] = 19.078 water use [mm] – 1820.4 under mulching practices. ASWC= available soil water content at sowing. acty =actual yield under conventional management practice; poty= attainable yield under conventional management practice; potym= attainable yield under mulching practices.

attainable yield at least 4000 kg ha^{-1} is 37.5 and 75 % for conventional management and mulching practices, respectively.

Use of frequency distributions of ASWC and yields

In order to calculate the actual probability of achieving at least a given spring wheat yield if the ASWC at sowing is unknown, the probability of obtaining that yield must be multiplied by the probability of achieving the ASWC at sowing. For example, the probability of obtaining a 2000 kg ha^{-1} actual yield with 120 mm of ASWC at sowing is 40 % times 80 % (Fig. 5 and Fig. 6b), 32 % under conventional management practice. With 160 mm of ASWC at sowing, the probability of obtaining 2000 kg ha^{-1} actual yield is 28 % times 70 % (Fig. 5 and Fig. 6c), 19.6 % under conventional management practice. However, the probability of obtaining 2000 kg ha^{-1} actual yield with 200 mm of ASWC at sowing is nearly approach zero. Because it is zero probability of achieving ASWC at sowing greater than 200 mm, although there is nearly 100 % of probability achieving a actual yield greater than 2000 kg ha^{-1} with given ASWC at sowing at 200 mm (Fig. 5 and Fig. 6d).

Discussion

The CWUPF for spring wheat in WLP was established using data collected from references. The slope of the production function for spring wheat (14.6 kg ha^{-1} mm^{-1}) was similar to the results in previous researches for wheat, 14.2 kg ha^{-1} mm^{-1} for bread wheat (Siahpoosh & Dehghanian, 2012), and 12.5 kg ha^{-1} mm^{-1} for winter wheat (Nielsen *et al.*, 2011). It represents a typical relationship between water use and grain yield for C3 plant, apparently smaller than the value for C4 plant: 28.1 kg ha^{-1} mm^{-1} for maize (Klocke *et al.*, 2014) and 30.2 kg ha^{-1} mm^{-1} for grain sorghum (Nielsen & Vigil, 2017a). It clearly verifies the statement that C3 plant has lower water use efficiency than C4 plant and C4 crop could produce more yields under same water use compared with C3 crop. Meanwhile, the x intercept (126.3 mm) in the current study was also similar to the value obtained in Moberly *et al.* (2017) for winter wheat and Zhang & Oweis (1999) for bread wheat.

The slope and x intercept for wheat is not identical from one research to another and several factors account for the difference. The slope of CWUPF for spring wheat during 1922-1952 was only 2.1 kg ha^{-1} mm^{-1} (Allison *et al.*, 1958), which was significantly lower than that for spring wheat in today, 14.6 kg ha^{-1} mm^{-1} in the current study. The great difference between the slope at that time and today could attribute to the improvement of genetic features and agricultural management. Meanwhile, Zhang & Oweis (1999) found that the slopes of two types of wheat growing under the same climate were significantly different from each other, due to varieties difference. Additionally, the tillage system and soil surface conditions also could affect the slope and x-intercept greatly. In the current study, with mulching practices, the spring wheat yield increased apparently compared with conventional management practice under the same water use (Fig. 4). It would also influence the water use-yield relation, hence the slope and x intercept of CWUPF. It is noteworthy that evaporative demand might be the most important factor affecting the slope of CWUPF (Nielsen & Vigil, 2017a). Slope of CWUPF could be calculated by following equation based on Eq. [1]:

$$Slope = \frac{DM}{T} HI = \frac{k}{\overline{E}_0} HI \qquad [2]$$

where *HI* is harvest index. From the equation, we could conclude that higher evaporative demand results in a smaller slope for a constant *HI*. It means the crop would have lower water use efficiency due to higher evaporative demand, which would induce much more soil water and precipitation fallen on the cropland loss directly by soil evaporation without formation of dry matter. Meanwhile, it indicates that x intercept could be larger under climate with higher evaporative demand. However, French & Schultz (1984) attributed the difference of x intercept in different areas to precipitation and soil types. In water-limited areas, evaporative demand is always much larger than precipitation, and there would be no further soil evaporation occurring as top soil layer drying out. Therefore, the evaporation from soil and hence the x intercept is indeed determined by precipitation and soil physical characteristic.

Previous researchers questioned the possibility of single CWUPF for a given location to be established. Meanwhile, from the discussion above and other's researches, we know a series of factors would affect the CWUPF. However, Huang *et al.* (2004) and Musick *et al.* (1994) found surprisingly constant water use-yield relations in their studies for specific plant species in same location during different years with a wide range of treatments (sowing date, planting density, water supply, nutrition, etc.). In the current study, we also found there was only one typical CWUPF established for spring wheat in the WLP with data collected from references during 1993-2013 with different wheat varieties under different climatic patterns (Figs. 1 & 3). The CWUPF was established based on data with enough fertilizer supply under conventional management practice in current study. Therefore, the available fertilizer and soil surface conditions have no effect on the relation between water use and spring wheat yield. Meanwhile, we found there was no significant trend for the spring wheat yield during 1987-2011 (Fig. S1f [suppl.]), and we speculated that there was no apparently genetic improvement for the spring wheat varieties during the period of our research. Hence, the difference of varieties would not influence CWUPF. Additionally, in the current study we found the climatic factors, excepted precipitation, seldom affect the spring wheat yield (the regression analysis results are not shown). It indicates that other climatic factors under extreme conditions occur seldom and they would not affect on crop production function for spring wheat in the study area, which contradicts the research of Nielsen & Vigil (2017b), in which water use-yield relation was affected greatly by a series of climatic factors, especially maximum temperature. Furthermore, in previous researchers, the non-linear relation between water use and crop yield is generally attributed to fluctuated soil evaporation which does not contribute to plant growth throughout the crop life cycle. In current study, the x intercept was 126.3 mm, which indicates the average soil evaporation during spring wheat growing season in the study area was about 126.3 mm. By using this value, we found the estimated water use also had significant relation with spring wheat yield for data collected from experiment and the slope and x intercept had no significant difference with the values obtained by data collected from references (Fig. 2). It clearly indicates that the x intercept we obtained represented the soil evaporation in this area for spring wheat growing season. Due to all of those reasons, the single CWUPF was established at WLP.

The potential transpiration efficiency of spring wheat estimated from boundary function in current study is apparently lower than the value in other researches. French & Schultz (1984) found that the potential transpiration efficiency of wheat was 20 kg ha^{-1} mm^{-1}. Later, Angus & Herwaarden (2001) stated the slope of boundary function approached to 22 kg ha^{-1} mm^{-1} due to genetic improvement of varieties compared with French & Schultz (1984). After then, a large number of researchers used this slope to define boundary function for wheat (Sadras & Angus, 2006; Zhang *et al.*, 2013). In our research, the boundary function was only 16.2 kg ha^{-1} mm^{-1} and 19 kg ha^{-1} mm^{-1} for conventional management practice and mulching practices, respectively. The spring wheat mainly grows during spring and summer with short growing duration, whereas the winter wheat grows during autumn, winter, spring and early summer with long growing duration. The different growing season might result in a different evaporative demand. Based on Eq. [2], under relatively hotter growing season with short duration for spring wheat, the potential transpiration efficiency would be smaller than the winter wheat.

Compared with conventional management practice, the practices with mulching increased spring wheat yields apparently (Fig. 4). And the probability for obtaining a given yield thresholds was higher for mulching practice than that of conventional management practice under same ASWC at sowing (Fig. 6). Meanwhile, the yield at 4000 kg ha^{-1} seems as a ceiling yield for actual spring wheat yield under conventional management practice without irrigation and the water use was hardly greater than 400 mm (Figs. 4 & 6d), which is similar to the long-term average yearly precipitation in the current study area. However, with mulching practices, the spring wheat yield increased to 4000 kg ha^{-1} with water use at 300 mm. By using mulching, much more soil water would be saved for transpiration to achieve more dry matter, not for useless soil evaporation (Li *et al.*, 2004). Meanwhile, mulching prevents weed growth, decreasing water wasted by weed transpiration, and much more water could be used for spring wheat growth. Furthermore, the soil temperature with plastic film mulching would improve the rate of seed germination and plant growth (Zhao *et al.*, 2012), which would result in spring wheat growing under a more suitable environmental condition before hot summer coming.

Soil storage before sowing is very critical for increase of spring wheat yield and assessment of agricultural input loss risk for agricultural producers in WLP. The current study clearly shows that the higher probability to obtain yield >2000 kg ha^{-1} occurs under condition with greater soil water content at sowing. With great soil water storage, spring wheat would grow fast and cover bare soil in a shorter time preventing useless evaporation from soil directly. Therefore, a greater share of soil water and precipitation would be used for wheat through transpiration for producing dry matter and grain yield. Meanwhile, the spring wheat has a relatively shorter growing season, about 120 days, and it would use soil water stored before sowing to establish a relatively higher leaf area index during vegetative stage, which would intercept much more radiation and produce higher dry matter and yield with supplement of precipitation during growing season (Lyon *et al.*, 1995). Furthermore, based on the amount of soil water storage and the frequency distributions of yield, it could help farmers in current study area to make decision, whether to sow spring wheat and apply fertilizer in the coming season for loss risk of agricultural input.

References

Allison FE, Roller EM, Raney WA, 1958. Relationship between evapotranspiration and yields of crops grown in lysimeters receiving natural rainfall. Agron J 50: 506-511.

Angus JF, Herwaarden AFV, 2001. Increasing water use and water use efficiency in dryland wheat. Agron J 93: 290-298. https://doi.org/10.2134/agronj2001.932290x

Connor DJ, Loomis RS, Cassman KG, 2011. Crop ecology: Productivity and management in agricultural systems. Cambridge Univ Press, Cambridge, UK, pp: 384-410.

Dai A, 2013. Increasing drought under global warming in observations and models. Nat Clim Change 3: 52-58. https://doi.org/10.1038/nclimate1633

De Wit CT, 1958. Transpiration and crop yields. In: Verslag. Landbouwk. Onderz. No. 64.6. Inst. of Biol. and Chem. Res. on Field Crops and Herbage. Wageningen, Netherlands, pp: 1-88.

Faci JM, Fereres E, 1980. Responses of grain sorghum to variable water supply under two irrigation frequencies. Irrigation Sci 1 (3): 149-159. https://doi.org/10.1007/BF00270879

French RJ, Schultz JE, 1984. Water use efficiency of wheat in a Mediterranean-type environment. I. The relation between yield, water use and climate. Aust J Agr Res 35: 743-764. https://doi.org/10.1071/AR9840743

Grassini P, Yang H, Cassman KG, 2009. Limits to maize productivity in Western Corn-Belt: A simulation analysis for fully irrigated and rainfed conditions. Agr Forest Meteorol 149 (8): 1254-1265. https://doi.org/10.1016/j.agrformet.2009.02.012

Hancock J, 2007. Water use efficiency of crops and pasture. In: Eyre Peninsula Farming Systems 2006 Summary; Cook A, *et al.* (eds). PIRSA Publ Services, South Australia.

Hanks RJ, Gardner HR, Florian RL, 1969. Plant growth evapotranspiration relations for several crops in the central Great Plains. Agron J 61: 30-34. https://doi.org/10.2134/agronj1969.00021962006100010010x

Hoffmann MP, Haakana M, Asseng S, Höhn JG, Palosuo T, Ruiz-Ramos M, Fronzek S, Ewert F, Gaiser T, Kassie BT, 2018. How does inter-annual variability of attainable yield affect the magnitude of yield gaps for wheat and maize? An analysis at ten sites. Agr Syst 159: 199-208. https://doi.org/10.1016/j.agsy.2017.03.012

Huang M, Gallichand J, Zhong L, 2004. Water-yield relationships and optimal water management for winter wheat in the Loess Plateau of China. Irrigation Sci 23: 47-54. https://doi.org/10.1007/s00271-004-0092-z

Huang Y, Chen L, Fu B, Huang Z, Gong J, 2007. The wheat yields and water-use efficiency in the Loess Plateau: Straw mulch and irrigation effects. Agr Water Manage 72: 209-222. https://doi.org/10.1016/j.agwat.2004.09.012

Kang S, Zhang L, Liang Y, Cai H, 2002. Effects of limited irrigation on yield and water use efficiency of winter wheat on the Loess Plateau of China. In: Regional water and soil assessment for managing sustainable agriculture in China and Australia; McVicar TR, *et al.* (eds), Acitar Monographs. Acitar, Canberra, Australia, pp: 105-116.

Kirkham M, 2005. Water and yield. In: Principles of soil and plant water relations. Dana Dreibelbis, Burlington, USA, pp: 469-484. https://doi.org/10.1016/B978-012409751-3/50027-X

Klocke NL, Currie RS, Kisekka I, Stone LR, 2014. Corn and grain sorghum response to limited irrigation, drought, and hail. Appl Eng Agric 30: 915-924. https://doi.org/10.13031/aea.30.10810

Legrand FE, Myers HR, 1973. Weather observation and use. In OSU Extension Facts No. 9410. Oklahoma State Univ, USA.

Li FM, Wang J, Xu JZ, Xu HL, 2004. Productivity and soil response to plastic film mulching durations for spring wheat on entisols in the semiarid Loess Plateau of China. Soil Till Res 78: 9-20. https://doi.org/10.1016/S0167-1987(04)00020-0

Lyon DJ, Boa F, Arkebauer TJ, 1995. Water-yield relations of several spring-planted dryland crops following winter wheat. J Prod Agric 8: 281-286. https://doi.org/10.2134/jpa1995.0281

Moberly JT, Aiken RM, Lin X, Schlegel AJ, Baumhardt RL, Schwartz RC, 2017. Crop water production functions of grain sorghum and winter wheat in Kansas and Texas. J Contem Water Res Educ 162: 42-60. https://doi.org/10.1111/j.1936-704X.2017.03259.x

Musick JT, Jones OR, Stewart BA, Dusek DA, 1994. Water-yield relationships for irrigated and dryland wheat in the U.S. southern plains. Agron J 86: 980-986. https://doi.org/10.2134/agronj1994.00021962008600060010x

Nielsen DC, Vigil MF, 2017a. Defining a dryland grain sorghum production function for the Central Great Plains. Agron J 109: 1582-1590. https://doi.org/10.2134/agronj2017.03.0131

Nielsen DC, Vigil MF, 2017b. Water use and environmental parameters influence proso millet yield. Field Crop Res 212: 34-44. https://doi.org/10.1016/j.fcr.2017.06.025

Nielsen DC, Vigil MF, Benjamin JG, 2011. Evaluating decision rules for dryland rotation crop selection. Field Crop Res 120: 254-261. https://doi.org/10.1016/j.fcr.2010.10.011

Nolan S, Unkovich M, Shen Y, Li L, Bellotti W, 2008. Farming systems of the Loess Plateau, Gansu Province, China. Agr Ecosyst Environ 124: 13-23. https://doi.org/10.1016/j.agee.2007.08.009

Patrignani A, Lollato RP, Ochsner TE, Godsey CB, Edwards JT, 2014. Yield gap and production gap of rainfed winter wheat in the Southern Great Plains. Agron J 106: 1329-1339. https://doi.org/10.2134/agronj14.0011

R Development Core Team, 2014: R: A language and environment for statistical computing, Vienna, Austria.

Robertson MJ, Kirkegaard JA, 2005. Water-use efficiency of dryland canola in an equi-seasonal rainfall environment. Aust J Agr Res 56: 1373-1386. https://doi.org/10.1071/AR05030

Sadras VO, Angus JF, 2006. Benchmarking water-use efficiency of rainfed wheat in dry environments. Aust J Agr Res 57: 847-856. https://doi.org/10.1071/AR05359

Siahpoosh MR, Dehghanian E, 2012. Water use efficiency, transpiration efficiency, and uptake efficiency of wheat during drought. Agron J 104: 1238-1243. https://doi.org/10.2134/agronj2011.0320

Varzi MM, 2016. Crop water production functions: A review of available mathematical method. J Agr Sci 8 (4): 76-83. https://doi.org/10.5539/jas.v8n4p76

Wang J, Liu W, Dang T, 2011. Responses of soil water balance and precipitation storage efficiency to increased fertilizer application in winter wheat. Plant Soil 347 (1-2): 41-51. https://doi.org/10.1007/s11104-011-0764-4

Whitbread A, Hancock J, 2008. Estimating grain yield with the French and Schultz approaches vs simulating attainable yield with APSIM on the Eyre Peninsula. Global Issues, Paddock Action, Proc 14th Aust Agron Conf, Adelaide, Australia.

Xie ZK, Wang YJ, Li FM, 2005. Effect of plastic mulching on soil water use and spring wheat yield in arid region of northwest China. Agr Water Manage 75: 71-83. https://doi.org/10.1016/j.agwat.2004.12.014

Yu Q, Li L, Luo Q, Eamus D, Xu S, Chen C, Wang E, Liu J, Nielsen D, 2014. Year patterns of climate impacts on wheat yields. Int J Climatol 34: 518-528. https://doi.org/10.1002/joc.3704

Zhang HP, Oweis TY, 1999. Water-yield relations and optimal irrigation scheduling of wheat in the Mediterranean region. Agr Water Manage 38: 195-211. https://doi.org/10.1016/S0378-3774(98)00069-9

Zhang S, Sadras V, Chen X, Zhang F, 2013. Water use efficiency of dryland wheat in the Loess Plateau in response to soil and crop management. Field Crop Res 151: 9-18. https://doi.org/10.1016/j.fcr.2013.07.005

Zhao H, Xiong YC, Li FM, Wang RY, Qiang SC, Yao TF, Mo F, 2012. Plastic film mulch for half growing season maximized WUE and yield of potato via moisture-temperature improvement in a semi-arid agroecosystem. Agr Water Manage 104: 68-78. https://doi.org/10.1016/j.agwat.2011.11.016