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Full Length Article

Closing the Yield Gap and Achieving High Water Use Efficiency with Field Management Practices in Dryland Wheat: A Case Study on the Loess Plateau

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Abstract

To determine how field management impacts water use of winter wheat, yield gaps and water use efficiency in dryland farming, yield gap analysis based on boundary line analysis was applied. The results showed that plastic film mulching during the fallow period increased evapotranspiration (ET) and wheat yield but had little influence on water use efficiency (WUE) and the yield gap. Compared with no tillage (NT), deep ploughing (DP) increased wheat yield without influencing ET and thus increased WUE. Subsoiling had little influence on the average yield, but it increased the possibility of obtaining a high yield. Compared with drill sowing (DS), drill sowing on plastic film (DSM) increased wheat yield with an increase in ET. DSM also reduced the yield gap to some extent. Appropriate fertilizer application rates are also important for reducing yield gaps. When the yield gap was the lowest, the respective nitrogen and phosphate application rates were 150 ha^{-1} and 180 ha^{-1}, respectively. In conclusion, yield gap analysis based on boundary line analysis makes it possible to evaluate how effectively water is used. This case study on the Loess Plateau showed that plastic film mulch and drill sowing on the edges of plastic film (P-DS) increased wheat yield but had little impact on the yield gap and WUE. Deep ploughing increased wheat yield and WUE and reduced the yield gap. Subsoiling (SS) had little impact on yield and WUE, but it increased the possibility of obtaining a higher yield and reduced the yield gap. Moreover, SS is a more effective technique in wet years than in dry years. © 2020 Friends Science Publishers

Keywords: Yield gap analysis; Boundary analysis; Dryland farming; Plastic film mulch; Deep tillage

Introduction

From a global perspective, arid and semiarid regions account for over 40% of the land in the world. Dryland farming is the main type of farming in these regions and plays an important role in food production (Farooq and Siddique 2017). Water is the limiting factor in dryland farming. Sustainable development of agriculture requires that water should be used effectively to produce more yields (Blum 2009). In a typical dryland farming system, evapotranspiration (ET) is often used to represent field water consumption (Ding *et al.* 2018). Crop growth requires a certain amount of water. Generally, the higher the ET is, the higher the yield will be (Stewart and Lal 2018). However, field water consumption is a complex process. ET can be simply divided into two parts: soil evaporation (E) and plant transpiration (T). At the same level of ET, the ratio of E and T can vary greatly (French and Schultz 1984). In most cases, E is insensitive to yield, and T is the key to crop growth and yield formation. Hence, in the field, crop yield under the same ET can change substantially (Grassini *et al.* 2011; Edreira *et al.* 2018), and T/ET can also vary greatly (van Ittersum and Cassman 2013; Zhou *et al.* 2016). Plotting yield against ET results in a scatter plot; theoretically, regression analysis can be used to determine the best-fit relationships between yield and ET. Since the data are spread out, the coefficient of determination is low, and such a relationship does not explain the complex effect of weather on growth and yield (Sadras and McDonald 2012). In that case, French and Schultz (1984) proposed the concept of a boundary line, where an upper boundary line is fitted to describe the relationship between yield and ET. Yield data lower than the boundary line are considered to be limited by factors other than water (Sadras and Angus 2006; Sadras and McDonald 2012). Such an approach has been acknowledged by many researchers, and the boundary function has been used in many regions and on many crops (Sadras and Angus 2006; Grassini *et al.* 2009; Zwart *et al.* 2010). Using the boundary line as a benchmark indicates whether water is used efficiently or not at a certain level of water consumption.

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The French & Schultz approach also provides a new way to calculate the potential crop yield (attainable yield per unit of water use) under water-limited conditions (French and Schultz 1984). Generally, the yield obtained in the field is lower than the potential yield. Therefore, there is a yield gap between the attainable yield and the actual yield. The yield gap of a crop is defined as the difference between the yield under optimum management practices (potential yield) and the average yield achieved (actual yield) (van Ittersum and Cassman 2013). Yield gap analysis is a concept that has attracted increasing attention in recent years (Hatfield and Beres 2019). It supports decision making in agricultural development and scientific research. The calculated yield gap differs based on the yield potential. The potential yield from agricultural systems can be defined at different levels, including light-limited potential yield, light- and temperature-limited potential yield, climate-limited potential yield and so on (Van Ittersum *et al.* 2013). In previous studies, different methods were applied to calculate the yield potential and the yield gap. These models include field surveys (Affholder *et al.* 2013), modelling based on field experiments (Affholder *et al.* 2013; Meng *et al.* 2013; van den Berg and Singels 2013) and satellite data (Lobell 2013); among these, crop modelling is the most popular method for yield gap analysis.

Boundary line analysis provides a new method of calculating the potential yield. It also presents a new way to calculate the yield gap. Hence, boundary line analysis has previously been used in yield gap analysis (Wang *et al.* 2017; Hajjarpoor *et al.* 2018; Lollato *et al.* 2019). Yield gap analysis based on boundary function analysis calls for a large amount of on-farm data to obtain representative results. The Loess Plateau is a typical dryland farming region. Since 2009, in order to improve the yield and water use efficiency in this region, our research team has carried out a series of experiments on dryland winter wheat in Wenxi County in Shanxi Province, China, and thus has collected a large amount of data. Our experiments have included different kinds of field management practices, such as fertilization, soil surface mulching, and tillage. Hence in this research, we intend to take the Loess Plateau as a case study for using boundary line analysis to analyse how the dryland winter wheat yield gap is influenced by field management.

Materials and Methods

Site description

The study was conducted at the experimental station of Shanxi Agricultural University in Wenxi County, Shanxi Province, China (35°20’N, 111°17’E, and elevation 639 m), which is located in the south-eastern part of the Loess Plateau. The soil type at the experimental site is classified as silty clay loam. The basic soil properties in the region at 0–20 cm depth are shown in Table 1. In the drylands of this region, a single crop of winter wheat followed by a summer fallow period is the primary annual cropping system.

The climate in Wenxi is a temperate continental monsoon climate, with a mean annual temperature of 12.6°C. All experiments were conducted on drylands. The average annual precipitation during 2009 and 2017 was 459 mm, 55% of which was concentrated during the fallow period for winter wheat. In 2010–2011 and 2014–2015, the proportion of precipitation during the fallow period accounted for as much as 75 and 71% of the annual precipitation, respectively (Fig. 1). The mean annual reference evapotranspiration (ET_0) is 1840 mm, and the mean annual sunshine duration is 2460 h.

Experimental information

From 2009 to 2017, a series of experiments related to improving yield and water use efficiency in Wenxi County in the southern area of the Loess Plateau were conducted. Based on the treatments, experiments were classified into four different management types: mulching, tillage, sowing method and seeding rate. Descriptions of the experiments are shown in Table 2.

Sampling and calculation

The soil water content was measured before sowing and after harvest using a gravimetrical method. A soil auger with a diameter of 5 cm was used to collect soil samples in the centre of each plot. The sampling interval was 20 cm down to a depth of 300 cm. Each soil sample was stored in an aluminium specimen box to resist evaporation and oven-dried at 105°C for 24 h. The ration between the lost weight and dry soil is soil water content. ET was calculated using Eq. 1:

$$\mathrm{ET} = \mathrm{SW_0} - \mathrm{SW_1} + \mathrm{P} - \mathrm{R} - \mathrm{D} \qquad \text{(Eq. 1)}$$

Where SW_0 is the soil water storage before sowing and SW_1 is the soil water storage after harvest. P is the precipitation during the wheat growth period, R is the soil surface runoff, and D is the deep percolation. Since the field was flat and the experimental plots were surrounded by ridges to prevent runoff, R was estimated to be 0 in this research. The groundwater table was deeper than 50 m in the research region, and no water percolated to the deep soil layer in our experimental field. D also tended to be 0. Eq. 1 can be simplified to Eq. 2.

$$\mathrm{ET} = \mathrm{SW_0} - \mathrm{SW_1} + \mathrm{P} \qquad \text{(Eq. 2)}$$

At harvest time, a sample plot of 1 m^2 in size in each experiment plot was sampled to determine the grain yield. The water use efficiency was calculated using Eq. 3.

$$\mathrm{WUE} = \frac{\mathrm{Yield}}{\mathrm{ET}} \qquad \text{(Eq. 3)}$$

Statistical analysis

Collected data were analysed using analysis of variance technique and difference between treatments were

Table 1: Main soil properties before sowing in 2009

Soil properties	Soil nutrients	Contents
Chemical properties	Organic matter (g kg^{-1})	11.88
	Total nitrogen (g kg^{-1})	0.61
	Alkali-hydrolysis nitrogen (mg kg^{-1})	38.62
	Available phosphorous (mg kg^{-1})	14.61
	Available potassium (mg kg^{-1})	238.16
	pH	8.08
Physical properties	Bulk density (g cm^{-3})	1.38
	Soil porosity (%)	45.35
	Capillary porosity (%)	38.78
	Field water holding capacity (v/v) (%)	30.00

Table 2: Descriptions of the experiments from 2009 to 2017 in Wenxi County

Management type	Treatments	Description	Years	Sample number
Mulch	M	0.02 mm thick plastic film was applied during the fallow period to prevent soil surface evaporation	2009-2014	67
	NM	No plastic film was used	2009-2014	29
Tillage	NT	The land was left untilled after harvest	2010-2017	19
	DP	In the mid-July after a rainfall event, the soil was ploughed to a depth of 25-30 cm with a tractor	2009-2017	71
	SS	In the mid-July after a rainfall event, subsoiling to a depth of 30-40 cm was performed with a tractor	2009-2016	60
Sowing methods	DS	Drill sowing without plastic film mulch	2011-2017	44
	P-DS	Drill sowing on the edges of plastic film (Plastic film covered soil surface until anthesis)	2011-2017	46
Seeding rate	H	112.5 to 120 kg ha^{-1}	2012-2017	17
	M	90 to 105 kg ha^{-1} to 105 kg	2012-2017	32
	L	60 to 75 kg ha^{-1}	2012-2017	22

Note that sample number represents the number of data points for a specific treatment.
M= Plastic film mulch; NM= No mulch; NT= No tillage; DP= Deep plough; SS= Sub-soiling; DS= Drill sowing; P-DS= Drill sowing on the edges of plastic film; H= High seeding rate; M= Mid seeding rate; L= low seeding rate

Table 3: Yield, ET and WUE under different management practices

Management type	Practice	ET (mm)		Yield (kg ha^{-1})		WUE (kg ha^{-1} mm^{-1})		N
		Range	Mean	Range	Mean	Range	Mean	
Mulching	M	238-787	492 a	2256-6908	4943 a	5.43-15.82	10.51 a	67
	NM	206-752	412 b	1925-5816	4016 b	6.16-14.53	10.27 a	29
Tillage	NT	303-716	479 b	2473-5719	4226 b	5.8-11.88	9.06 b	19
	DP	206-775	474 b	2381-6628	4945 a	5.97-15.82	11.28 a	71
	SS	273-770	502 a	1386-6382	4101 b	2.59-13.61	8.25 b	60
Sowing Method	DS	273-736	406 b	1635-5576	3995 b	3.84-16.64	10.12 a	44
	P-DS	273-782	438 a	1769-6807	4688 a	4.58-18.40	10.91 a	46
Seeding Rate	H	313-605	462 a	1385-5360	3939 b	2.59-15.65	8.95 b	17
	M	312-596	428 b	1803-6807	4418 a	3.52-18.40	10.62 a	32
	L	297-585	440 ab	1515-5725	4236 a	2.89-17.01	10.19 a	22

Values of the same management type sharing same letters differ non-significantly ($P \le 0.05$)
N= Number of samples which represents the number of data points for a specific treatment; ET= Evapotranspiration; WUE= Water use efficiency; M= Plastic film mulch; NM= No mulch; NT= No tillage; DP= Deep plough; SS= Sub-soiling; DS= Drill sowing; P-DS= Drill sowing on the edges of plastic film; H= High seeding rate; M= Mid seeding rate; L= low seeding rate

compared using LSD (least significant difference) test at $P \le 0.05$ using SAS 9.0. Graphs were constructed using Microsoft Excel 2010 and sigmaPlot 12.0.

Results

Water use, yield and WUE under different management practices

Since the experiments were carried out in different years and both precipitation and temperature varied among the years, the ET, yield and WUE of the crops varied greatly (Table 3). Under plastic film mulching, the mean ET was 492 mm, which is 80 mm higher than that under no mulching. The wheat yield from mulching was 927 kg ha^{-1} higher than that from NM. Moreover, the lower limit and higher limit of yield under M also increased. The WUE was calculated as the ratio of yield to ET. The results showed that the WUE under M was to the same as that of NM.

Among the three tillage methods, SS resulted in the highest ET (502 mm), while the average ET for NT and DP was almost the same (479 and 474 mm, respectively). The mean yield was the highest for DP among the tillage methods. The WUE for NT, DP and SS was 9.06 kg ha^{-1}, 11.28 kg ha^{-1} and 8.25 kg ha^{-1}, respectively. Compared with DS, P-DS increased ET slightly (32 mm on average). The yield under P-DS was 4688 kg ha^{-1} on average, 692 kg ha^{-1} higher than the 3995 kg ha^{-1} yield under DS. The higher

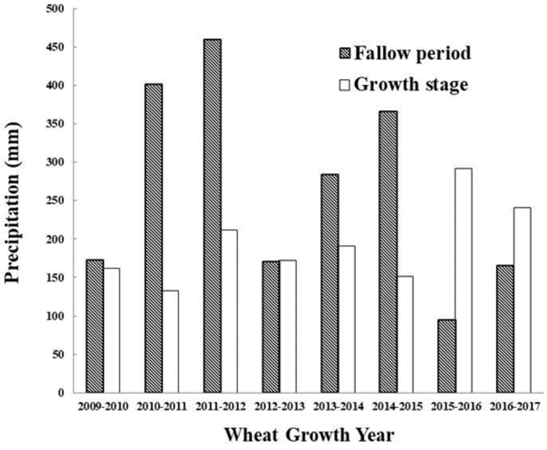

Fig. 1: Precipitation during wheat growth years from 2009 to 2017. The fallow period represents the time from the harvest of the previous season to the sowing of the current season.

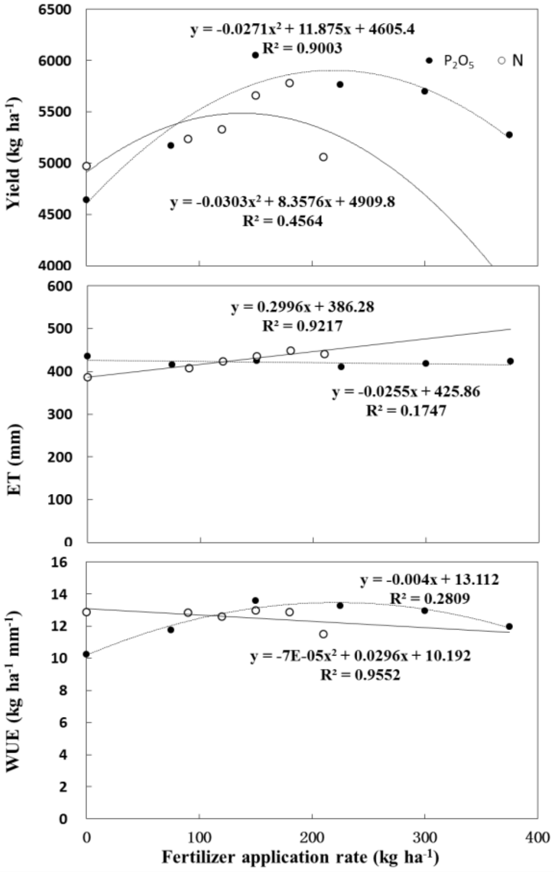

Fig. 2: Yield, ET and WUE at different fertilizer application rates
Phosphatic fertilizer application rate is calculated as the weight of P_2O_5 and nitrogen fertilizer application rate is calculated as the weight of pure nitrogen
ET= Evapotranspiration; WUE= Water use efficiency

yield led to a higher WUE in P-DS. The mean yield was highest at the moderate seeding rate, with a value of 4418 kg ha^{-1}. With the increase in seeding rate, the ET increased. A higher ET did not lead to higher yield. The WUE among the different seeding rates showed the opposite trend as yield, *i.e.*, the WUE was highest at the moderate seeding rate and lowest at the high seeding rate.

Wheat yield first increased with increasing fertilizer input and reached a peak before dropping again (Fig. 2). The yield peaked around the application rates of 150 and 200 kg ha^{-1} for N and P, respectively. ET increased slightly as the N application rate increased, but there was no evidence for the impact of P application on ET in this research. With the increase in P application, WUE showed a similar trend as yield, and the peak value for WUE also occurred at approximately 200 kg ha^{-1}.

Boundary analysis of the Y-ET relationship

The observed experimental data from 2009 to 2017 showed that during the experimental years, ET and yield varied greatly. Even at the same level of ET, a broad range of wheat yields were obtained. However, when all the data were plotted on a scatter diagram, a clear boundary emerged (Fig. 3). Based on the boundary function concept proposed by French and Schultz (French and Schultz 1984) and the improved boundary function establishment method developed by Lin and Liu (2016), we obtained the winter wheat boundary function for yield-ET at our research site. When ET is below 393 mm, the water-limited potential yield can be calculated as yield = 23.6 (ET-104.5). When ET is above 393 mm, the potential yield reached a plateau at 6807 kg ha^{-1} and no longer changed with the increase in ET. The boundary line also shows that when ET < 393 mm, the potential yield and WUE increase as ET increases; when ET > 393 mm, the potential remains stable, while the potential WUE decreases as ET increases. The potential WUE (WUE$_{max}$, dashed line in Fig. 3) shows that when ET<393 mm, WUE$_{max}$ increases as ET increases, while when ET>393 mm, WUE$_{max}$ decreases as ET increases. When ET>393 mm, the dashed line is a hyperbolic curve with a slope equal to the slope of the boundary line (23.6).

Yield gap analysis

The gap analysis showed that even though 393 mm is a threshold for water use in this dryland farming area, the yield gap was lower for the lower water consumption group than for the higher water use group (Fig. 4). For the mulching method, the yield gaps for M and NM were 1249 and 1280 kg ha^{-1}, respectively, which means that the plastic film mulching did not have a significant influence on the yield gap. Similar results were found with the sowing method. The yield gaps for DS and P-DS were 1971 and 1511 kg ha^{-1}, respectively. The yield gap among different tillage methods varied greatly. DP showed the lowest yield, with a value of 935 on average. The mean yield gaps for NT and SS were similar, with values of 2027 kg ha^{-1} and 2426 kg ha^{-1}, respectively. Compared with those under NT and DP, the yield gap of SS varied greatly, ranging from 330 kg ha^{-1} to 5326 kg ha^{-1}.

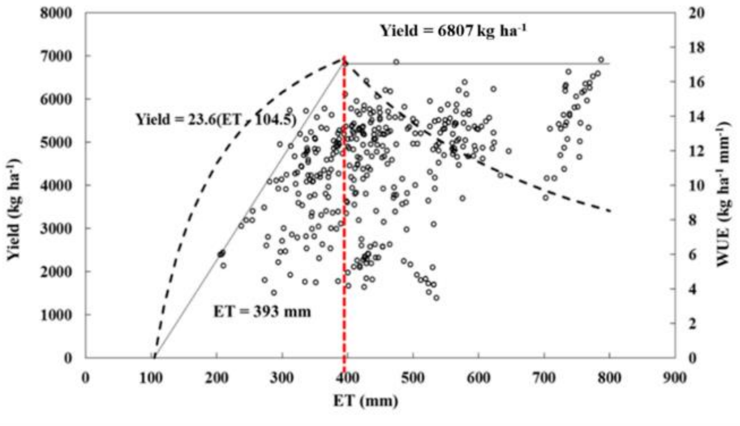

Fig. 3: Yield-ET relationship within a boundary framework (the solid line represents the upper boundary of yield, and the dashed line represents the corresponding WUE of the upper boundary). ET is evapotranspiration, WUE is water use efficiency

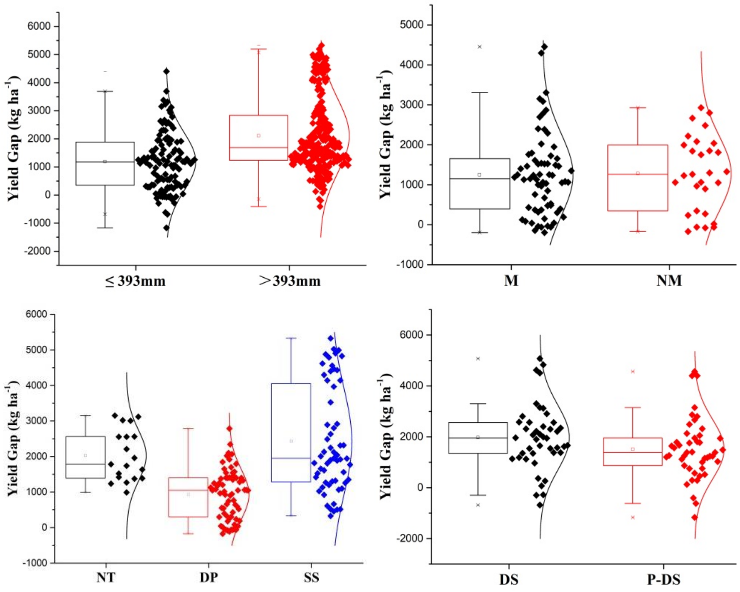

Fig. 4: Yield gap under different management methods

The dots to the right of each box represent the distribution of the data

M= Plastic film mulch; NM= No mulch; NT= No tillage; DP= Deep plough; SS= Sub-soiling; DS= Drill sowing; P-DS= Drill sowing on the edges of plastic film

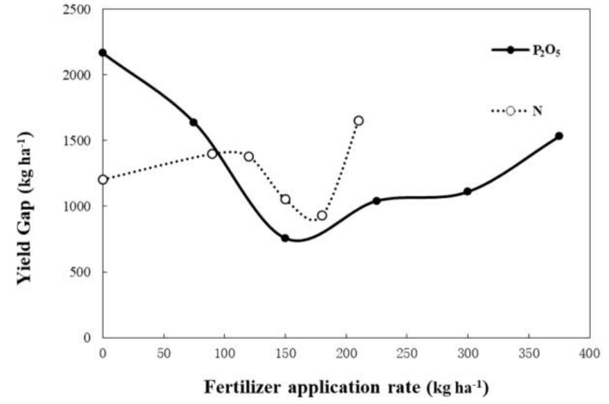

Fig. 5: Yield gap under different fertilizer application rates

Phosphatic fertilizer application rate is calculated as the weight of P_2O_5 and nitrogen fertilizer application rate is calculated as the weight of pure nitrogen

To analyse the impact of fertilization on the yield gap, we further analysed the yield gap under different nitrogen and phosphate application rates (Fig. 5). The results showed that with the increase in the N fertilization application rate, the yield gap showed a decreasing trend and reached its lowest value of 928 kg ha^{-1} at 180 kg ha^{-1}, after which it increased dramatically to 1651 kg ha^{-1} when the N application rate increased to 210 kg ha^{-1}. A similar trend was found for P application. The yield gap dropped from 2441 kg ha^{-1} to 1062 kg ha^{-1} and reached its lowest value when the P application rate increased from 0 to 150 kg ha^{-1}. When the P application rate rose from 150 to 375 kg ha^{-1}, the yield gap increased.

Discussion

In this research, we used field experimental data from a dryland farming system and drew an upper boundary in the yield-ET plot based on the French & Schultz framework as improved by Lin and Liu (2016). This upper boundary represents the on-farm potential yield under water-limited conditions. Generally, given a specific ET, the actual yield is lower than the potential yield. The gap between these two yield values is the yield gap. Such a boundary approach was used widely in the agricultural research.

In 2013, Zhang *et al.* (2013) collected the experimental yield and water use data for winter wheat on the Loess Plateau. In that research, Zhang suggested that the boundary function yield = 22 (ET-60) from Sadras and Angus (2006) reflects the situation on the Loess Plateau. In this research, the function of the boundary line was yield = 23.6 (ET-104.5), which is similar to those results. However, differences still exist. Our research showed a higher slope and a higher intercept. A higher slope indicates higher potential yield in this region, and a higher ET intercept means that more water is needed to obtain the yield. In Sadras' research, the boundary line represents the conditions in 4 mega-environments. In this study, all the data were obtained from a single site that represents the precise conditions in Wenxi County on the southern Loess Plateau, where the annual precipitation is 459 mm. Lower precipitations usually leads to high potential evapotranspiration (ET_0). A high ET_0 means that water is prone to loss due to soil evaporation; hence, the ET intercept is higher than that in other regions. The difference between our results and those of most previous boundary analysis studies is that the boundary line in this study reaches a plateau (6807 kg ha^{-1} when ET $\geq$ 393 mm). This means that in dryland farming, crop yield does not continuously increase with the increase in ET. When < 393 mm, water is the limiting factor that prevents the achievement of maximum yield. Appropriate field management practices help to make full use of the limited water and obtain the maximum yield under a specific water input level. When ET $\geq$ 393 mm, water is no longer the limiting factor for the maximum yield. During this stage, effective methods should be applied to reduce soil evaporation and hence reduce ET to improve WUE.

The results in this study showed that the impact of agronomy management practices on the yield, yield gap and WUE differed greatly. Plastic film mulching increased grain yield but also increased ET and showed little impact on WUE and yield gap. It seems that this is not an effective way to improve water use in this region. However, the plastic film was laid down during the fallow period, when a large proportion of the annual precipitation occurred (Fig. 1). Plastic film mulch reduces soil evaporation and conserves water in the soil (Li *et al.* 2013). Previous studies have shown that under plastic film mulching, soil water storage in the 0–300 cm soil layer increased by 0.37–9.75% in wet years and by 1.83–16.07% in dry years (Li *et al.* 2018). As more water was in reach of crop roots, more water was consumed during this growth period. In our study, the increased proportion of ET and the increase in yield were similar, which led to almost no change in the WUE. According to the study of Blum (2009), the effective use of water, rather than the WUE, is the target for crop yield improvement under drought stress. In terms of the yield gap under PM, though PM led to little improvement in the yield gap, it improved the yield level. A low yield gap with a high yield level is the optimum result, but an unchanged yield gap with an improved yield level is also considered a success in field management.

Among the three tillage methods, DP led to the highest average yield during the experiments (Table 2). Moreover, the yield gap under DP was also the lowest (Fig. 4). For SS, the average yield and yield gap were close to those under NT. Compared with that under NT, the yield under SS showed a wider range (1386–6382 kg ha^{-1}), which means that SS has the potential to obtain a higher yield at our research site. In fact, under SS, the soil water infiltration ability improved, and hence, during wet years, more water was available for crops (Li *et al.* 2014). However, in dry years, this factor is not significant, and hence, the yield was not improved. The yield gap analysis shows that under DP, the lowest yield gap was approximately 800 kg ha^{-1}, which was lower than that under NT. This result illustrates that, compared with NT, SS has greater potential to reduce the yield gap.

Such a yield gap analysis provides a new method for field water management. The most important thing is to reduce yield gap, increase WUE to make “more crop per drop” (Blum 2009). However, if WUE is used as the single standard for benchmarking crop yield, it will lead to mistakes in field management. In Fig. 3, if we draw a line that goes through the origin and passes through as many dots as possible, all the dots on the line will have the same WUE. However, crop WUE increased with increasing drought stress and reduced water supply (Stewart and Lal 2018); hence, low ET may also lead to high WUE. Low

ET with low yield will not provide the farmer with enough food, despite the high WUE. The yield gap for a particular ET provides an additional way to benchmark crop management (Sadras and Angus 2006). For a given ET, the yield gap illustrates how high of a yield is high enough. The yield gap also indicates how much the yield can be improved. If a yield gap exists, it means that the water was not used effectively and that there must be constraints other than water (Grassini *et al.* 2009).

At last, it should be noted that, though yield helps to benchmark field water use in dryland faming, it does not replace WUE. The shortcoming of the yield gap is that at the same yield gap value, the ET varies greatly. On the Loess Plateau in this study, at 200 mm of ET with a yield of 1754 kg ha^{-1} and at 300 mm ET with a yield of 4114 kg ha^{-1}, the yield gaps were both 500 kg ha^{-1}. Clearly, 300 mm ET with 4114 kg ha^{-1} yield is more acceptable for farmers and researchers.

Conclusion

Appropriate field management can improve yields and reduce yield gaps. Plastic film mulch in the fallow period and drilling sowing without plastic film mulch increased wheat yield but had little impact on yield gap and WUE. Deep ploughing increased wheat yield and WUE and reduced the yield gap. Subsoiling had little impact on yield, WUE and yield, but it increased the possibility of obtaining a higher yield and reduced the yield gap. Subsoiling is a more effective technique in wet years than in dry years. Yield gap analysis provides a supplemental method for evaluating water productivity in dryland farming. At the same level of WUE, a higher yield gap indicates a higher yield. With the same yield gap, the higher the WUE is, the higher the yield will be.

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Author Contributions

Conceived and designed the experiments: Min Sun, Wen Lin and Zhiqiang Gao. Performed the experiments: Hao Li, Jie Zhao, Aixia Ren. Analysed the data: Hao Li, Jie Zhao, Wen Lin. Wrote the paper: Hao Li, Jie Zhao. All authors discussed the results and commented on the contents of the manuscript.

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