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Contribution of Subsoiling in Fallow Period and Nitrogen Fertilizer to the Soil-water Balance and Grain Yield of Dry-land Wheat

Min Sun, Zhi-qiang Gao*, Ai-xia Ren, Yan Deng, Wei-feng Zhao, Hong-mei Zhao, Zhen-ping Yang, Li-heng He and Yu-zhen Zong

College of Agriculture, Shanxi Agricultural University, Taigu 030801, Shanxi Province, PR China

*For correspondence: gaozhiqiang1964@126.com

Abstract

Soil water conservation is crucial to the yield of dry-land wheat. The aim of this study was to explore an effective method to improve the water conservation and wheat yield in the Loess Plateau of Shanxi, China. A two-factor split-plot design was performed in field with tillage practice (subsoiling and no tillage) as main plot and nitrogen (N) application (75, 150 and 225 kg·hm^{-2}) as subplot. Soil water storage (SWS), yield and its components, and precipitation use efficiency (PUE) were determined. In fallow period, subsoiling increased the SWS in the 0–300 cm soil depth. In the growth period, subsoiling not only had a positive effect on water storage at the over-wintering, jointing and booting stages, but also accelerated the water utilization in the 0–60 cm soil depth during sowing-jointing and jointing-anthesis stage and in the 180–300 cm depth during anthesis-maturity stage. Consequently, yield and PUE were significantly improved by increasing the spike number and grain number per spike. Soil water storage declined as the concentration of N increased. Moreover, subsoiling in fallow period combined with 150 kg·hm^{-2} N significantly increased the water utilization in the 0–60 cm depth at the early vegetative growth stage, enhanced the water absorption by deep roots at late reproductive growth stages, improved yield by increasing spike numbers and had a strong positive effect on PUE. Application of 150 kg·hm^{-2} N notably enhanced the promoting effects of subsoiling on soil water conservation, water utilization and yield of dry-land wheat.

Keywords: Dry-land wheat; Fallow period; Subsoiling; N application; Grain yield; Soil-water balance

Introduction

Water is one of the main constraints to productivity and quality of wheat, and precipitation represents the main water source in dry-land wheat, which is widely grown in the Loess Plateau of China (Timsina *et al.*, 2001; Cabrera-Bosquet *et al.*, 2007). About 60–70% of annual precipitation occurs in fallow period from July to September in dry-land wheat (Zhang *et al.*, 2013). The uneven distribution of rainfall and high evaporation in fallow period make it difficult to satisfy the crop water requirements during the plant growth stages, leading to the decrease in grain yield. Hence, improving water conservation within the soil profile is crucial to increase the yield of dry-land wheat.

Many studies have demonstrated that soil water storage (SWS) was significantly related to tillage practices, such as no tillage (NT) and subsoiling (SS) (Jin *et al.*, 2007; Hou *et al.*, 2012). It has been reported that NT management decreases soil disturbance and reduces soil bulk density (Zhang *et al.*, 2007). Application of SS, which loses soil without turnover and breaks plow pan, can improve SWS by facilitating infiltration (Mohanty *et al.*, 2007). In the Loess Plateau area of Henan Province in China, SS in summer fallow period resulted in the highest precipitation storage efficiency (PSE), precipitation use efficiency (PUE) and crop yield compared to other tillage practices (Jin *et al.*, 2007).

Nitrogen (N) is an essential mineral nutrient for plant growth and development. N fertilizer improves soil fertility and crop productivity (López-Bellido *et al.*, 2012; Wang *et al.*, 2012; Ahmad *et al.*, 2013). Interactions between water and N fertilizer are complicated and may cause either positive or negative effects on plant growth and crop yield (Halvorson *et al.*, 1991; Li *et al.*, 2009; Khan *et al.*, 2014). Studies have demonstrated that under proper irrigation condition, increasing the level of N supply promoted the root development and N absorption (Halvorson *et al.*, 1999; Morell *et al.*, 2011), enhanced the osmotic adjustment capability, and inhibited transpiration (Zhang *et al.*, 2002). Nevertheless, at present, most studies mainly focused on the relationship between water irrigation and N fertilization, and few studies have investigated the interaction among precipitation, fertilization, water conservation and crop production. In this study, we investigated the effects of SS and N fertilization rate on SWS, PUE and grain yield in the Loess Plateau of Shanxi, China, to explore a valid water conservation method combined with an appropriate rate of N-application to improve the yield of dry-land wheat.

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Materials and Methods

Experimental Field

The experiment was conducted between 2010 and 2011 in the Wenxi Experimental Station of Shanxi Agricultural University (35.35°N, 111.22°E), which is located in the dry-land cropping region of the Loess Plateau in Shanxi, China. This site has a warm temperate continental climate with an annual mean precipitation of 506 mm, an annual mean temperature of 12.5°C and an open pan evaporation of 1357.10 mm. The soil properties tested in July 2010 were (organic matter, 8.65 $g \cdot kg^{-1}$; total N, 0.74 $g \cdot kg^{-1}$; available N, 32.93 $mg \cdot kg^{-1}$; available phosphorus, 20.08 $mg \cdot kg^{-1}$). The data of precipitation at the experimental site including fallow period (from early July to early Oct), from sowing to over-wintering stage (from early Oct to late Nov), from over-wintering to jointing stage (from late Nov to early Apr in the following year), from jointing to anthesis stage (from early Apr to early May), and from anthesis to maturity (from early May to mid-Jun) were recorded.

Experimental Design

'Yunhan 20410', a cultivar of winter wheat (*Triticum aestivum*) provided by Wenxi agriculture bureau, was used in this study.

The layout for the experiment was a two-factor split-plot design with tillage practice in main plots and N application in subplots, with three replicates. The experimental treatments included were 2 tillage practices, SS and NT with three N rates (NH_4NO_3 75, 150 and 225 $kg \cdot hm^{-2}$). Each subplot was 5 m wide and 10 m long.

Stubble (about 20 cm high) remained in fields after wheat harvest. About 2 weeks later, SS was performed by a subsoiling fertilization machine (1ST-4Ⅱ, Liming Machinery Manufacturing Co., Ltd., Jilin, China) to a depth of 30–40 cm on 1st July, 2010. On 20th August, rotary tillage was carried out to crumble large lumps, level the fields and improve soil moisture. Phosphatic (P_2O_5 150 kg hm^{-2}), potash (K_2O 150 kg hm^{-2}) and different rates of N (NH_4NO_3 75, 150 and 225 kg hm^{-2}) fertilizers were applied just before sowing. The seeds were sown in the experimental field at rate of 225×10^4 hm^{-2} with a row spacing of 20 cm on 29th September.

Sampling and Measurement

Sampling and measurement were performed in fallow period (from early July to early Oct) and during different plant growth stages (sowing stage, early Oct; over-wintering stage, late Nov; jointing stage, early Apr in the following year; anthesis stage, early May; maturity stage, mid-Jun). The SWS and water storage efficiency (WSE) were measured according to the previous studies (Ferraro and Ghersa, 2007; Hou *et al.*, 2012). Soil samples were taken in 20 cm increments from 0 to 300 cm during the fallow period and different growth stages of dry-land wheat from each subplot. The soil samples were weighed wet, dried in oven at 105°C for 48 h, and weighed again to determine the soil water content and soil bulk density. Soil bulk density was expressed as the dry weight per unit volume of soil ($g \cdot cm^{-3}$). The SWS in fallow period and at different wheat growth stages were calculated as below:

Soil water content (%) = (Wet weight-Dry weight)/Dry weight×100.

SWS (mm) = Soil water content × Soil profile depth×Soil bulk density.

WSE in fallow period was calculated as below:

$$WSE = \Delta SWS/P_f \times 100\%.$$

ΔSWS, SWS increment from the beginning to the end of fallow period in the 0–300 cm soil depth; P_f, precipitation in fallow period.

At maturity stage, yield components, including spike number, grain number per spike and thousand-grain weight, were determined in a 20 m^2 area of each subplot (Bustos *et al.*, 2012). Grain yield was calculated as below:

Grain yield = Spike number × Grain numbers per spike × Thousand-grain weight/1000.

Precipitation potential use efficiency (PPUE) and PUE was estimated as below (Hu *et al.*, 2010):

$$PPUE = [P_g \times (1-\gamma_g)+P_f \times (1-\gamma_f)-ET_f]/P \times 100\%.$$

P_g, precipitation during wheat growing period; P_f, precipitation during fallow period; γ_g, runoff coefficient during wheat growing period; γ_f, runoff coefficient during fallow period; P, annual precipitation; ET_f, evapo-transpiration during the fallow period.

PUE = Grain yield/P. P, annual precipitation.

Statistical Analysis

All data were expressed as means ± SD. Differences were compared by t-test or one-way ANOVA followed Duncan's multiple-range test using SAS 9.0 software (SAS Corp, Cary, NC, USA). Correlation between variables was assessed using Pearson's correlation coefficient within SAS. Comparisons with $P<0.05$ were considered significantly different.

Results

Precipitation Distribution

Precipitation in the experimental field during fallow period and different growth stages of wheat during the study period and previous 5 years are shown in Table 1. The precipitation during 2010–2011 received (534.70 mm) was higher than the mean annual precipitation in the previous 5 years (405.49±39.40 mm) ($P<0.05$).

Table 1: Precipitation at the experimental site

Year	Precipitation (mm)					
	Fallow period	Sowing-Over-wintering	Over-wintering-Jointing	Jointing-Anthesis	Anthesis-Maturity	Total
2005–2010	227.58±30.46	46.90±9.84	35.50±12.84	34.06±0.09	61.44±5.89	405.49±39.40
2010–2011	401.50	27.10	19.10	22.20	64.80	534.70

Data source: Meteorological station of Wenxi County, Shanxi, China

Table 2: Effects of subsoiling on soil water storage in the 0-300 cm depth in fallow period of dry-land wheat

Tillage	P_f (mm)	SWS_f (mm)		WSE (%)
		Initial stage	Terminal stage	
SS	401.50	289.00	442.96±4.68	38.35±1.17*
NT			406.44±3.15	29.25±0.79

SS, subsoiling; NT, no tillage; P_f, precipitation in fallow period; SWS_f, soil water storage in fallow period; WSE, water storage efficiency

The precipitation in fallow period was higher than at growth stages, accounted for 75% and 58% of annual precipitation during the study period and the previous 5 years, respectively.

Effects of Subsoiling on SWS in Fallow Period

SWS at the soil depth of 0–300 cm were tested in the fields with or without subsoiling treatment (Table 2). The results showed that in fallow period, SS increased the SWS by 36.52 mm, and the WSE was significantly increased by 31.10% ($P<0.05$).

Effects of SS and N Fertilizer on SWS at Different Wheat Growth Stages

We found that SS significantly increased the SWS at the over-wintering, jointing and booting stages ($P<0.05$), except at booting stage when high level of N was applied (Table 3), suggesting that enhanced effect of SS on the water storage maintained to the booting stage of dry-land wheat. As the concentration of N increased, the SWS declined in plots under subsoiling treatment at the over-wintering, jointing, booting and anthesis stages of dry-land wheat, while similar pattern was observed in the non-tilled fields at the over-wintering, jointing and booting stages (Table 3).

The SWS was decreased with the growth of wheat, and a minimal level of SWS was observed at maturity stage. Therefore, the effect of SS on decrease rate of SWS was investigated at different soil depths during the early vegetative growth period (from sowing to jointing stage), the middle growth period (from jointing to anthesis stage) and the late productive period (from anthesis and maturity stage) (Fig. 1). The results showed that SS accelerated the decrease rate of SWS in the 0–60 cm soil depth during sowing-jointing stage (Fig. 1A), and significantly increased in the 0–60 cm depth during jointing-anthesis stage (Fig. 1B) and in the 180–300 cm depth during anthesis-maturity stage (Fig. 1C). The decrease rate of SWS during sowing-jointing stage in the 0–120 cm depth declined as concentration of N increased (Fig. 1A). In the 0–120 cm soil depth, the decrease rate of SWS during jointing-anthesis stage was significantly higher under the moderate and high N levels than under the low level of N treatment (Fig. 1B). Similar pattern was observed in the 180–240 cm soil depth during anthesis-maturity stage (Fig. 1C).

Effects of SS and N Fertilizer on Yield of Dry-land Wheat

We found that SS significantly increased the spike numbers, grain numbers per spike and yield under all tested N treatments, and thousand-grain weight at low N application ($P<0.05$) (Table 4). Spike numbers and yields in all tested subplots were highest under moderate level of N, and lowest when low level of N was applied.

Correlation Analysis Between the Decrease Rate of SWS and Yield Components

To further investigate the relationship between the decreased rate of SWS at different growth stages in different soil depths and yield, a correlation analysis was performed (Table 5). The results showed that during sowing-jointing stage, spike number, grain number per spike, and yield had a positive correlation with the decrease rate of SWS in 0–180 cm and 240–300 cm depths, the 0–180 cm depth, and the 60–120 cm depth ($P<0.05$), respectively. During jointing-anthesis stage, spike number showed a positive correlation with the decrease rate of SWS in the 0–60 cm depths ($P<0.01$), and grain number per spike and yield were positively correlated with the decrease rate in the 0–120 cm depth ($P<0.05$). During anthesis-maturity stage, spike number were negatively correlated with the decrease rate in 0–60 cm and 120–180 cm soil depths ($P<0.05$), while grain number per spike, thousand-grain weight and yield showed a negative but not significant correlation.

Effects of SS and N Fertilization on Rainfall Use

In addition, SS in fallow period significantly increased the PPUE by 15% (Table 5). The PUE at all tested N levels were also markedly enhanced by SS ($P<0.05$). The PUE at moderate level of N was highest, while lowest efficiency was found at low level of N (Table 6), indicating that subsoiling combined with application of 150 $kg \cdot hm^{-2}$ N was optimum.

Table 3: Effects of subsoiling and nitrogen fertilizer on soil water storage in the 0-300 cm depth at different growth stages of dry-land wheat

Tillage	N supply (kg hm^{-2})	SWS (mm)				
		Over-wintering	Jointing stage	Booting stage	Anthesis	Maturity
Sub-soiling	75	414.35±1.00 *a	378.75±2.18 *a	341.25±1.30 *a	313.09±2.93 a	268.41±1.36 a
	150	402.85±4.00 *b	370.12±1.28 *b	325.71±0.87 *b	294.11±2.49 b	253.73±4.79 b
	225	382.06±2.62 *c	344.07±2.76 *c	293.10±2.86 c	281.22±2.87 c	245.07±1.48 b
No tillage	75	394.72±0.89 a	365.09±1.64 a	321.64±1.82 a	306.04±2.39 a	262.36±2.84 a
	150	384.52±4.14 b	352.39±3.09 b	309.93±0.46 b	284.99±6.14 b	247.98±4.30 b
	225	369.69±2.78 c	338.78±4.43 c	302.77±0.50 c	279.24±4.24 b	238.24±1.74 b

Differences between subsoiling and no tillage were compared with t-test. *p<0.05 and **p<0.01 vs. NT
Differences of different nitrogen application rates were compared with Duncan's multiple-range test, and average values followed by the same letter are not significantly different (α=0.05)

Table 4: Effect of subsoiling and nitrogen fertilizer on yield and its component of dry-land wheat

Tillage	N supply (kg hm^{-2})	Spike number ($10^4 hm^{-2}$)	Grain number per spike	Thousand-grain weight (g)	Yield (kg hm^{-2})
Sub-soiling	75	403.46±3.13 *c	27.50±0.06 *b	38.98±0.20 *b	4121.54±18.69 *c
	150	428.04±0.29 *a	28.25±0.64 *ab	41.40±0.52 a	4462.42±43.76 *a
	225	411.37±1.39 *b	29.49±0.52 *a	40.55±0.43 a	4214.40±6.58 *b
No tillage	75	392.68±3.45 b	26.16±0.72 a	37.35±0.14 b	3241.39±32.09 c
	150	405.04±0.29 a	25.71±0.30 a	40.81±0.01 a	3689.17±89.82 a
	225	399.62±3.54 ab	25.61±0.68 a	41.05±0.11 a	3511.03±13.05 b

Differences between sub-soiling and no tillage were compared with t-test. *p<0.05 and **p<0.01 vs. NT
Differences of different nitrogen application rates were compared with Duncan's multiple-range test, and average values followed by the same letter are not significantly different (α=0.05)

Table 5: Correlation analysis between the decrease rate of soil water storage at different growth stages and yield

Growth stage	Soil depths (cm)	Spike number	Grain number per spike	Thousand-grain weight	Yield
Sowing–Jointing	0-60	0.8793**	0.7664*	0.6307	0.7305
	60-120	0.9324**	0.9051**	0.4927	0.8283*
	120-180	0.9457**	0.8804**	0.4218	0.6892
	180-240	0.6335	0.3310	0.5698	0.1569
	240-300	0.8985**	0.7276	0.7412	0.7422
Jointing–Anthesis	0-60	0.9259**	0.8710*	0.5726	0.9236**
	60-120	0.6695	0.9216**	0.0187	0.8415*
	120-180	-0.0758	-0.1596	0.5808	0.4052
	180-240	-0.1602	0.0063	0.1422	0.4086
	240-300	-0.5832	-0.5642	0.1890	-0.1491
Anthesis–Maturity	0-60	-0.8720*	-0.6205	-0.3229	-0.3406
	60-120	-0.6037	-0.2491	-0.2560	0.0169
	120-180	-0.8299*	-0.4495	-0.5803	-0.4063
	180-240	0.5375	0.2637	0.2999	0.0642
	240-300	0.0316	0.3320	-0.7114	0.0037

Correlation between variables was assessed using Pearson's correlation coefficient within SAS. Comparisons with P<0.05 were considered significantly different. *P<0.05; **P<0.01

Table 6: Effects of subsoiling and N fertilizer on rainfall use in dry-land wheat

Tillage	N supply (kg hm^{-2})	P_f (mm)	P_g (mm)	PPUE (%)	PUE (kg·hm^{-2}·mm^{-1})
Sub–soiling	75	401.50	133.20	53.70±0.88*	7.71±0.03 *c
	150				8.35±0.08 *a
	225				7.88±0.01 *b
No–tillage	75			46.87±0.59	6.06±0.06 c
	150				6.90±0.17 a
	225				6.57±0.02 b

Differences between subsoiling and no tillage were compared with t-test. *p<0.05 and **p<0.01 vs. NT
Differences of different nitrogen application rates were compared with Duncan's multiple-range test, and average values followed by the same letter are not significantly different (α=0.05)
P_f, precipitation during fallow period; P_g, precipitation during growing period; PPUE, precipitation potential use efficiency; PUE, precipitation use efficiency

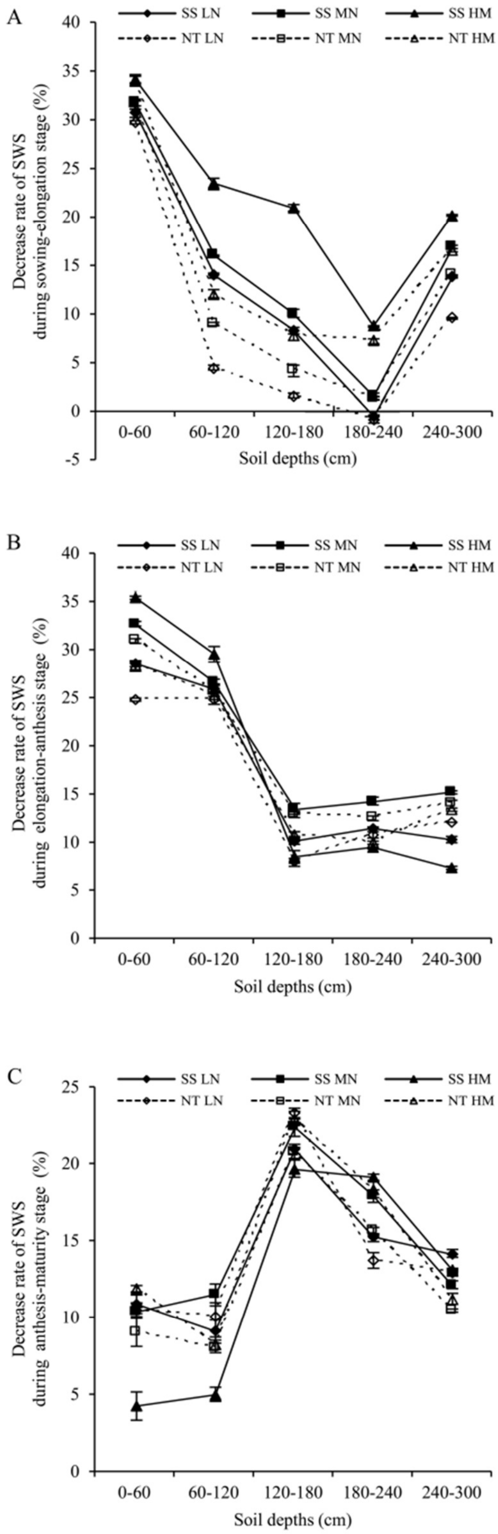

Fig. 1: Effect of subsoiling and nitrogen fertilization on decrease rate of soil water storage at different growth stages in dry-land wheat

Decrease rate of soil water storage during sowing-elongation (A), elongation-anthesis (B) and anthesis-maturity (C) stages were calculated in different soil depths of each subplot. SWS, soil water storage

Discussion

It has been reported that wheat in eastern part of the Loess Plateau of China needs about 480 mm water for maximum yield (Wang, 1994). Although the annual precipitation during 2010 to 2011 was 534 mm at the experimental site of this study, it was mainly concentrated in fallow period (Table 1). Thus, improving water conservation within the soil profile is crucial to increase the yield of dry-land wheat.

Many evidences have demonstrated that water storage was significantly related to tillage practice (Jin *et al.*, 2007; Hou *et al.*, 2012). In our study, SS was performed 2 weeks after the previous crop harvested. We found that SS had a beneficial effect on SWS and WSE in fallow period, indicating that SS could create favorable conditions for timely sowing and subsequent germination of dry-land wheat. Our findings further supported the contribution of SS to water storage. Similar results were observed in the fallow period of 2009–2010. However, soil degradation caused by continuous tillage is known to reduce water-use efficiency and crop yield (Cabrera-Bosquet *et al.*, 2007). It has been reported that interval of NT and SS could improve soil physical and chemical properties, and thus significantly increase crop yields and water-use efficiency (Cabrera-Bosquet *et al.*, 2007). Thus, it needs to be further explored whether successive SS or interval of NT and SS is suitable for the wheat growth in the Loess Plateau area of Shanxi Province in China.

Earlier reports indicate that tillage increased SWS in 0–200 cm soil depth at the whole growth stages of wheat (Deng *et al.*, 2011). In our study, SS showed significant positive effects on SWS in the 0–300 cm soil depth from the over-wintering to anthesis stage, but not at the maturity stage. Further study demonstrated that SS accelerated the water utilization at 0–60 cm depth during the early and middle growth stages of wheat and promoted the water usage in deep soil layers (180–300 cm). Wheat plants utilize water from shallow soil layer (0–50 cm depth) at the seedling stage, while water from middle and deep layers (50–200 cm depth) was absorbed at the late vegetative growth stages and the reproductive growth stage (Wang *et al.*, 2012) confirms present study findings. After application of SS, soil become loosen and plow pan is broken, which improves SWS by facilitating infiltration (Mohanty *et al.*, 2007). During later growth stages of wheat, the root systems are well developed to utilize the water stored in middle and deep layer.

Furthermore, we found that increasing the level of N supply had a significant negative effect on SWS in the 0–300 soil depth at the over-wintering, jointing and booting stages in the non-tilled plots, while this regulatory effect of N application extended to the anthesis stage when SS was performed in fallow period of dry-land wheat. Application of moderate N rate significantly enhanced the SS-increased water utilization in the 0–60 cm soil depth at the early and middle growth stage of wheat, which contributed to increase of spike number, optimization of the yield structure, and thereby improvement of the yield. In addition, moderate level of N treatment promoted the SS-increased water absorption in the 180–240 cm soil depth at the late productive growth stage, which improved the PUE. However, high N level negatively affected the yield and PUE compared to the moderate N level. N fertilization is a common practice to increase crop production, but the optimum N fertilization rate varies depends on soil water status which influences the osmotic potential (Li *et al.*, 2009; Guo *et al.*, 2012). The results indicated that SS in fallow period combined with moderate level of N (150 $kg \cdot hm^{-2}$) had the strongest effect on the yield of dry-land wheat by increasing the spike numbers.

Conclusion

In conclusion, we demonstrated that SS exhibited beneficial effects on SWS, yield and PUE, which could be enhanced by application of 150 $kg \cdot hm^{-2}$ N. Our findings had significant implications for optimizing tillage practice and N fertilization rate, and maximizing grain yield and PUE in dry-land wheat in the Loess Plateau of Shanxi, China.

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