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Effects of different straw mulch modes on soil water storage and water use efficiency of spring maize (*Zea mays* L.) in the Loess Plateau of China

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ABSTRACT

The effects of different modes of straw mulch on soil water storage, grain yield and water use efficiency (WUE) of spring maize (*Zea mays* L.) were evaluated from 2007–2010 at the Dry Farming Base of Northwest A&F University, in the Loess Plateau of China. Seven treatments were conducted, including conventional tillage without straw mulch (CK), maize straw mulch for the whole year (WSM) at the rates of 4 500, 9 000 (S2) and 13 500 kg/ha (S3), and maize straw mulch only during growth period (GSM) at the rates of 4 500, 9 000 and 13 500 kg/ha. The results showed that the 3-year average soil water storage within the 200 cm soil depth for the WSM was increased when compared to the CK and GSM; the three-year average grain yield increased with straw mulch rate, and WSM and GSM increased the average grain yield by 4.4% and 2.0% when compared to CK; the WUE were also increased in straw mulch treatment; however, there were no significant differences in the grain yield and WUE between the S2 and S3. Therefore, the WSM mode with maize straw mulch rate of 9 000 kg/ha was preferable for the Loess Plateau of China with the precipitation lower than 390 mm during the growth period of spring maize.

Keywords: soil water content; water shortage; crop productivity; subarid region

Water shortage is one of the major problems limiting crop productivity in arid and semi-arid regions (Tavakkoli and Oweis 2004). Crop productivity could be greatly influenced by even a small change in soil water storage (Liu et al. 2010). Cover with crop straw on soil surface – straw mulch – is considered important to promoting soil moisture content (Li et al. 2012), improving crop yields and water use efficiency (WUE) (Wang et al. 2009). Generally, soil water storage kept improving when straw mulch was applied, Liu et al. (2010) found that straw mulch with 6000 kg/ha improved 30 mm

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soil water storage in the profile of top 200 cm. Li et al. (2013) reported that soil mulched with wheat straw conserved 106.9 mm water in the 0–200 cm soil layer during the maize growth stage. In addition, several studies reported that crop yields were increased by straw mulch (Liu et al. 2010, Wang et al. 2012); however, different or conflicting results were also found, for example, Gao and Li (2005) reported that the straw mulch with winter wheat remarkably decreased the crop yields. Because soil water storage in arid regions is significantly influenced by straw mulch, there is an increasing requirement for understanding the responses of soil water dynamics and crop productivity to straw mulch, and a lot of methods have been applied to study the effects of straw mulch on soil properties and crop productivity (Sapkota 2012, Kahlon et al. 2013). However, the important problem to be solved in these studies is how to choose mulch modes for getting the optimal effect.

The Loess Plateau of China is the largest loess plateau around the world, which is located in the northeast of China with 400 000 square kilometers. The fluctuant and uneven seasonal distribution of rainfall has a great impact on the growth of spring maize, which is the main crop in this area. Straw mulch has been carried out in this region to improve crop yields (Liu et al. 2010, Cai et al. 2011, Li et al. 2012), however, the effects of straw mulch on soil water storage, spring maize yield and WUE are not well documented. Especially, the rate and time of the optimal straw mulch mode are still not clear. Therefore, the main objectives of this study were to (1) clarify the responses of soil water, spring maize yield and WUE to different straw mulch modes, and (2) provide optimal mode of the straw mulch for the Loess Plateau of China.

MATERIAL AND METHODS

Study area. Field experiments were conducted at the Rained Experimental Station of Northwest Agriculture and Forestry University of Science and Technology, located in the Loess Plateau in northeast China (34°15'N, 106°30'E). The study area is located in a typical subhumid arid zone, and has adequate light and heat resources, the annual precipitation and potential evapotranspiration are 538.2 mm and 1832.8 mm, respectively, 60% of precipitation occurr from July to September (Figure 1a), the annual average temperature is 10.5°C (Figure 1b). The soil type is sandy loess soil, the percentage of sand, silt and clay are 80.9, 12.5, 6.6, respectively. The average soil bulk density was 1.35 g/cm^3 and average field water capacity of the 0–200 cm soil was 29.84% volumetrically. The total organic matter, total N, total P and total K of the soil were 10.9, 0.8, 0.6 and 7.1 g/kg, respectively; the nitrate nitrogen, ammonia nitrogen, available P and available K were 24.61, 1.95, 11.57 and 113.79 mg/kg, respectively; the pH value was 8.1.

Experimental design. Three rates of straw mulch designed to explore the optimal straw mulch rate for this region were 4500, 9000, and 13 500 kg/ha. The experiment was started from spring 2007 when the maize was seeded to autumn 2010 when the maize was harvested. Each plot measured 8 m × 5 m and was separated by concrete walls. The experiment contained seven treatments with three replications. The WSM mode was maize straw mulch for the whole year (straw mulch during the fallow period and the maize growing period) with three mulch rates (4500, 9000 and 13 500 kg/ha), which were presented as S1, S2 and S3, respectively. The GSM mode was maize straw mulch only during the growth period, it also had three mulch rates (4500, 9000 and 13 500 kg/ha), which were designated as S4, S5 and S6, respectively. In addition, the conventional tillage without straw mulch was conducted as the control (CK). The WSM mode was conducted as follows: straw mulch in the winter fallow period was performed after the previous maize harvesting. The previous mulch straw without decomposing in soil surface was chopped and mixed with the 15–20 cm soil via tillage before the maize was seeded. After that, the collected maize straw was re-distributed evenly in the plots. GSM mode was as follows the plots were covered by maize straw after maize was seeded, and the straw was removed after maize harvesting. All treatments were conducted at the same plots for three years. According to the local practice, urea (total N ≥ 46.4%) 525.0 kg/ha, diammonium hydrogen phosphate (DAP) (total nutrients ≥ 60.0%, N-P-K: 17-43-0) 326.7 kg/ha, KCl (K_2O ≥ 60.0%) 330.0 kg/ha were applied before maize were seeded. Each plot was then compacted and leveled. Spring maize seed was manually drilled in furrows with row spacing of 67.5 cm × 30 cm in all treatments. The cultivar of spring maize was Yuyu 22 and its population was about 49 500 plants/ha.

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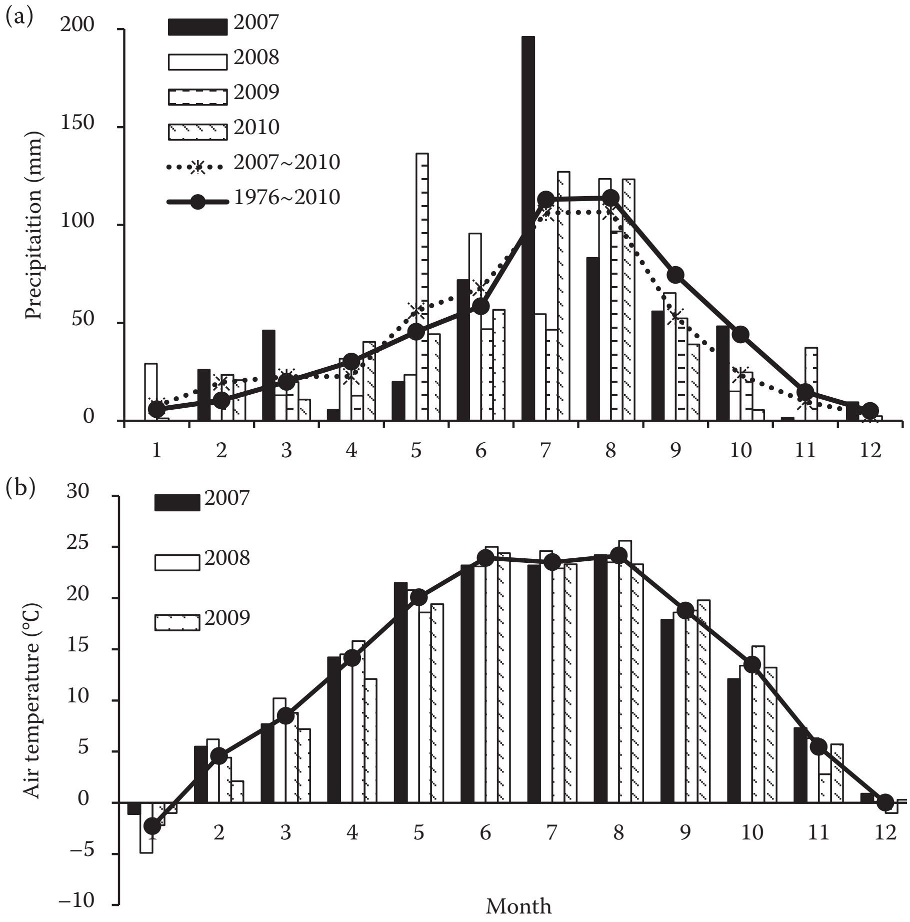

Figure 1. Distribution of the monthly precipitation (a) and air temperature (b) in different years and their average value at the study area

During the growing period, all plots received none additional fertilization or supplementary irrigation. Maize was seeded on May 25–30 and harvested on September 17–20 every year.

Measurements. The soil sampling was performed before seeding and at harvest, and five samples in each plot were taken at depth intervals of 20 cm for a profile of 0–200 cm. All soil samples were bulked and transported to the laboratory, the soil water content was determined gravimetrically by oven-drying (105°C for 24 h), and field capacity was measured as the gravimetric water content of saturated soil that was allowed to drain for 6 h in a filter funnel jars with soil equilibrated in darkness (15 days at 25°C), periodically adjusting soil moisture based on weight loss. The soil bulk density was measured by the method of cutting ring. The soil water storage (W) and yield WUE were described according to Nyakudya and Stroosnijder (2014). Due to the deep underground water (> 50 m) of the study area, the underground water supply was ignored. The water balance equation was simplified as follows:

$$W = \sum_{i=1}^{n} (h_i \times \rho_i \times \theta_{m_i}) \times 10 \quad (1)$$

$$ET = (W1 - W2) + P \quad (2)$$

$$WUE = Y/ET \quad (3)$$

Where: W (mm) – soil water storage for 0–200 cm profile; h (cm) – depth interval for soil sample; ρ (g/cm^3) – soil bulk density; θ_m – soil gravimetric water content (%), subscript *i* referred to the soil layer; *n* – number of soil layers; ET (mm) – evaporation of water from the soil surface plus transpiration from the crop; W1, W2 (mm) – 0–200 cm soil water storage before spring maize seeding and after harvesting; P (mm) – precipitation; WUE (kg/ha/mm) – yield water use efficiency; Y (kg/ha) – grain yield.

The maize plants at the edge of the plot were removed at the harvest time to reduce edge effects, and maize was harvested from 21 m^2 in each plot to determine grain yield, all grain samples were natural drying in the same environment to ensure the same moisture.

Data analysis. Data analysis was performed using ANOVA with SAS 8.01 software (SAS Institute Inc., Cary, USA). Statistical significance (P < 0.05) was determined using the *LSD* method.

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RESULTS AND DISCUSSION

Soil water storage and soil gravimetric water content in the 0–200 cm profile. The water storage of the soil from 0–200 cm was not only affected by the natural precipitation, but it was also influenced by the rate and the time of straw mulch (Table 1). The greatest loss of soil water in CK was in the period of 2007–2008, followed by 2009–2010 and 2008–2009, and the average moisture loss for the three years was 10.3 mm. Under the WSM mode, from 2007–2010, the soil water storage showed a reduction for S1, but increased gradually for S2 and S3 (no significant difference between S2 and S3). Under the GSM mode, the variation of the soil water storage was similar to those of the WSM, but the soil water storage was less (no significant difference between S5 and S6). Compared to the CK, both WSM and GSM showed stronger water storage, the soil water storage of the WSM was significantly greater than that of the GSM.

The soil gravimetric water content in the 0–200 cm profile at harvest from 2008–2010 is shown in Figure 2. The differences of soil gravimetric water content between CK and straw mulch were greatest in 2010, followed by 2008, and then 2009. Compared with CK, soil gravimetric water content was improved in the 0–200 cm profile by straw mulch, due to the deep underground water supply was ignored, the more water loss in CK was consumed by evaporation in surface. The soil moisture easily reached to the upper soil layer through by the capillary in the sandy loess soil, then more water from deep layer moving up to surface and consumed by evaporation, which resulted in less water retaining in the soil in CK. The change of average soil gravimetric water content of GSM was less than that of WSM. The order of the average water gravimetric content of the 0–200 cm profile in the seven treatments were S3 > S2 = S6 > S5 > S1 > S4 > CK, which indicated that the average soil gravimetric water content of WSM was always better than GSM excepted for S1 and S4, and the soil water storage showed a positive correlation with the mulch rate.

Grain yield and water use efficiency. The grain yields of S2 and S3 were significantly higher than those of CK in 2008 and 2010, however, the treatments of straw mulch showed no significant differences with CK in 2009 (Figure 3). It was due to precipitation from June to August in 2008, 2009 and 2010 that were 273.6, 190.2 and 307.3 mm (Figure 1), respectively. This period of time included the critical growth stages of jointing, booting and filling for spring maize, and the decrease of the precipitation in 2009 reduced the effect of straw mulch on the grain yield.

The three-year average grain yield increased with straw mulch rate, and WSM and GSM increased the average grain yield by 4.4% and 2.0% when compared to CK. When the mulch rate was less than 9000 kg/ha, the increase of the mulch rate significantly increased the maize grain yield; however,

Table 1. Variation of soil water storage (mm) at the 0–200 cm soil profile in different treatments from 2007–2010

Mulch mode	Treatment	2007 harvest	2008 before seeding	2008 harvest	2009 before seeding	2009 harvest	2010 before seeding
Non-mulch	CK	506.5^{b} ± 2.6	485.8^{c} ± 2.1	430.3^{b} ± 3.9	426.0^{c} ± 2.6	421.7^{c} ± 1.7	415.7^{c} ± 2.4
	S1	513.8^{b} ± 2.4	507.4^{b} ± 2.4	439.5^{b} ± 2.7	438.9^{b} ± 1.1	429.1^{b} ± 2.8	428.0^{b} ± 1.9
WSM	S2	518.3^{ab} ± 2.3	514.6^{a} ± 0.5	445.1^{a}b ± 1.2	445.9^{ab} ± 2.4	436.7^{ab} ± 1.4	441.0^{ab} ± 2.7
	S3	524.1^{a} ± 0.3	523.8^{a} ± 0.5	453.1^{a} ± 3.4	455.0^{a} ±3.1	441.6^{a} ± 3.2	446.0^{a} ± 4.2
Non-mulch	CK	506.5^{b} ± 2.6	485.8^{c} ± 2.1	430.3^{b} ± 3.9	426.0^{c} ± 2.6	421.7^{c} ± 1.7	415.7^{c} ± 2.4
	S4	510.7^{b} ± 2.2	495.8^{b} ± 1.9	432.5^{b} ± 1.7	430.1^{b} ± 2.7	423.1^{b} ± 4.2	420.2^{b} ± 4.1
GSM	S5	517.3^{a} ± 0.2	514.6^{a} ± 2.5	442.6^{a} ± 3.6	441.6^{ab} ± 3.8	433.4^{a} ± 3.7	435.0^{a} ± 2.8
	S6	518.2^{a} ± 0.9	516.0^{a} ± 3.0	447.8^{a} ± 4.3	449.3^{a} ± 4.2	438.6^{a} ± 5.3	440.7^{a} ± 3.4

Values are mean ± standard error. Different lowercase letters in the same column with each mulch model denote significant differences ($P < 0.05$) compared to CK treatment. CK – without straw mulch; WSM – maize straw mulch for whole year at the rates of 4 500 (S1), 9 000 (S2) and 13 500 kg/ha (S3); GSM – maize straw mulch only during growth period at the rates of 4 500 (S4), 9 000 (S5) and 13 500 kg/ha (S6)

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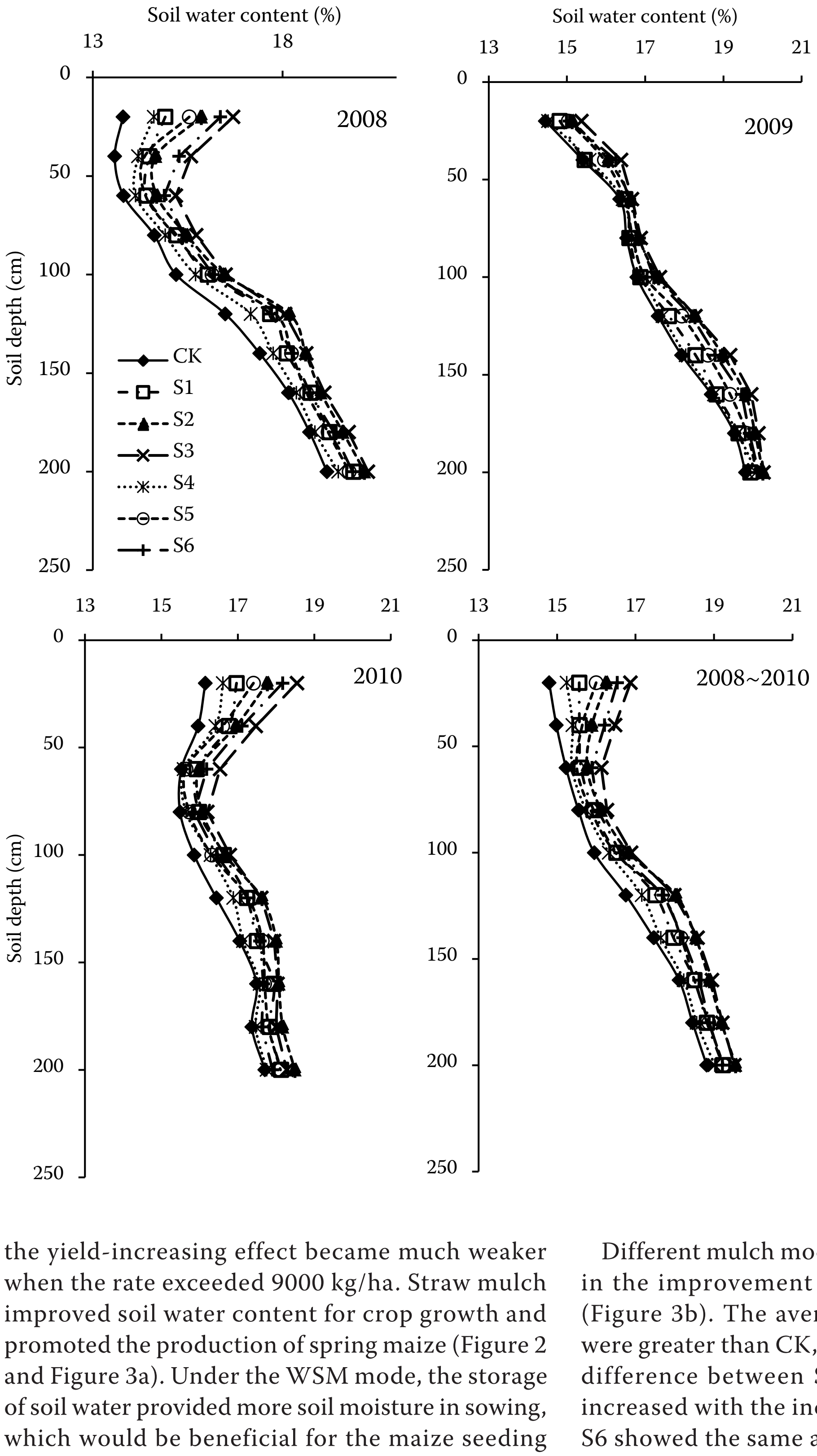

Figure 2. Soil gravimetric water content and their average value in profile at harvest with different treatments in 2008–2010. CK – without straw mulch; maize straw mulch for whole year at the rates of 4 500 (S1), 9 000 (S2) and 13 500 kg/ha (S3); maize straw mulch only during growth period at the rates of 4 500 (S4), 9 000 (S5) and 13 500 kg/ha (S6)

the yield-increasing effect became much weaker when the rate exceeded 9000 kg/ha. Straw mulch improved soil water content for crop growth and promoted the production of spring maize (Figure 2 and Figure 3a). Under the WSM mode, the storage of soil water provided more soil moisture in sowing, which would be beneficial for the maize seeding and for promoting the emergence and survival rate of the maize. Therefore, straw mulch treatments had a significant yield-increasing effects in arid regions (Edwards et al. 2000).

Different mulch modes showed large differences in the improvement of WUE in different years (Figure 3b). The average WUE in S1, S2 and S3 were greater than CK, and there was no significant difference between S2 and S3. WUE gradually increased with the increase of mulch rate; S5 and S6 showed the same average WUE with the value of 19.5 kg/ha/mm, which was higher than that of S4. Under the WSM mode, the greatest WUE was presented in 2010, followed by 2008, and then 2009. Overall, WUE of the WSM was higher than

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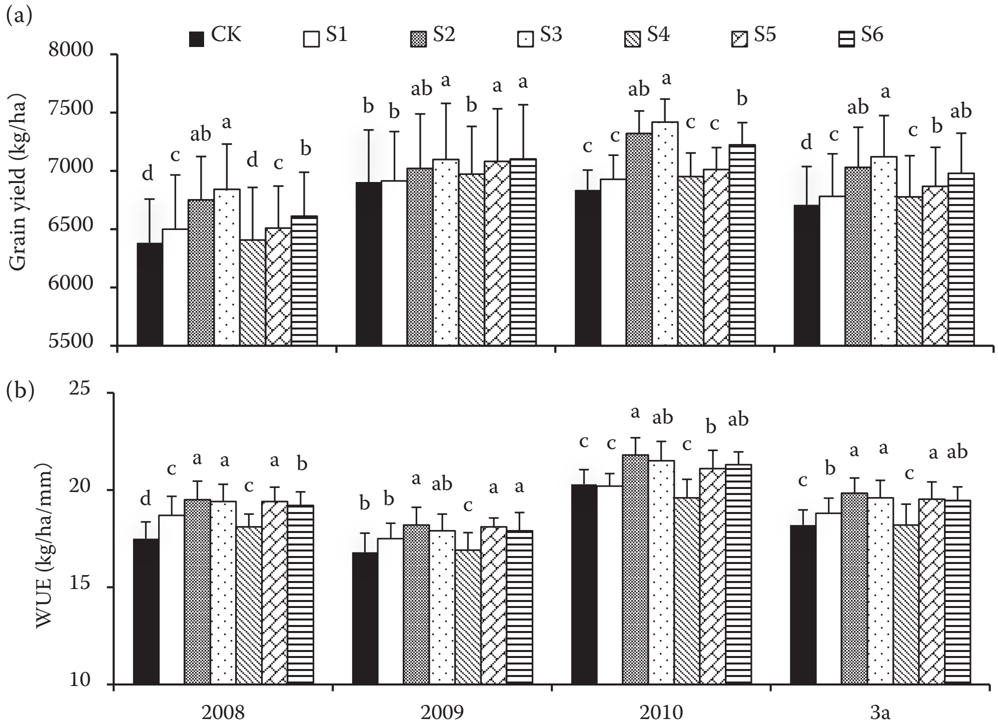

Figure 3. (a) Spring maize grain yield and (b) water use efficiency (WUE) of spring maize and their average value (3a) with different treatments in 2008–2010. CK – without straw mulch; maize straw mulch for whole year at the rates of 4 500 (S1), 9 000 (S2) and 13 500 kg/ha (S3); maize straw mulch only during growth period at the rates of 4 500 (S4), 9 000 (S5) and 13 500 kg/ha (S6)

that of the GSM. Considering the effects of WSM on the yield, the optimal rate of mulch should be 9000 kg/ha.

In conclusions, in the present study, the soil moisture, maize production and WUE under the WSM mode showed changing patterns similar to those of the GSM mode, but with lower changing rates. The average soil water storage of WSM was always better than GSM, and the soil water storage showed a positive correlation with the mulch rate, which indicated that the WSM, especially the S2 and S3 treatments, should be the optimal mulch mode for maintaining soil moisture in the Loess Plateau of China. The mulch at the rate of 4500 kg/ha did not show an obvious influence on the yield-increase and WUE, while the mulch at the rate of 13 500 kg/ha had a negative influence on maize seeding and early growth. The mulch at the rate of 9000 kg/ha showed the optimal impacts on water storage, maize yield and WUE. Therefore, the WSM mode with the rate of 9000 kg/ha should be the optimal pattern for straw mulch in Loess Plateau of China with the precipitation below 390 mm during the growth period of spring maize.

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