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Tillage and straw mulching impacts on grain yield and water use efficiency of spring maize in Northern Huang–Huai–Hai Valley

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A B S T R A C T

A two-year field experiment (2012–2013) was conducted to investigate the effects of two tillage methods and five maize straw mulching patterns on the yield, water consumption, and water use efficiency (WUE) of spring maize (*Zea mays* L.) in the northern Huang–Huai–Hai valley of China. Compared to rotary tillage, subsoil tillage resulted in decreases in water consumption by 6.3–7.8% and increases in maize yield by 644.5–673.9 kg ha^{-1}, soil water content by 2.9–3.0%, and WUE by 12.7–15.2%. Chopped straw mulching led to higher yield, soil water content, and WUE as well as lower water consumption than prostrate whole straw mulching. Mulching with 50% chopped straw had the largest positive effects on maize yield, soil water content, and WUE among the five mulching treatments. Tillage had greater influence on maize yield than straw mulching, whereas straw mulching had greater influence on soil water content, water consumption, and WUE than tillage. These results suggest that 50% chopped straw mulching with subsoil tillage is beneficial in spring maize production aiming at high yield and high WUE in the Huang–Huai–Hai valley.

1. Introduction

Food security is challenged by increasing global population, climate change, and resource shortages [1,2]. In particular, severe water scarcity occurs in 45% of the global land resources [3]. The Huang–Huai–Hai valley is one of the major grain production areas in China, with a traditional double cropping system of winter wheat (*Triticum aestivum* L.)–summer maize (*Zea mays* L.). In recent years, water shortage has become the most important constraint to agriculture in this area [4]. Since the late 1980s, high temperature, high evaporation levels, and uneven distribution of rainfall have resulted in more frequent droughts during the maize-growing season, affecting the stability of food production [5,6]. More than 70% of irrigation water are used during the winter wheat season [7]. Recently, spring maize cultivated from the end of March to May has been introduced to serve as an alternative crop to winter wheat–summer maize because it produces 76.7% of the annual grain yield and reduces irrigation water consumption by 50% compared to the winter wheat–summer maize cropping system

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[8]. However, yields in the spring maize cropping system consistently account for only 56.9–66.3% of those in the winter wheat–summer maize system in the Huang–Huai–Hai valley, owing mainly to drought stress [9]. Thus, optimal agronomic practices are desirable for the new cropping system.

Subsoil tillage (ST) and straw mulching are typical cultivation methods used to improve crop yields in arid areas [10,11] and may mitigate drought in the spring maize season. After ST, soil moisture content increased [8], and water infiltrated into deep soil layers [11–13]. With ST, the final yield of spring maize may be markedly improved. Straw mulching can reduce evaporation, increase soil moisture content, and enhance maize growth and development, leading to increased grain yield and water use efficiency (WUE) [4,14,15]. However, the quantity of straw mulch used should be limited within a certain range to prevent deleterious effects on seedling growth, WUE, and ultimately crop productivity [16,17]. The form of straw residue also alters the soil microclimate. Normally, straw mulching is expected to reduce the temperature at 0–10 cm soil depth, to reduce evaporation, and to increase dry matter accumulation during the growth period [18].

In this study, we conducted a two-year field experiment to investigate ST and straw mulching techniques in spring maize in the north Huang–Huai–Hai valley. To our knowledge, this is the first report on the effects of ST combined with straw mulching on spring maize yield and WUE in the Huang–Huai–Hai valley, where drought seriously affects the stability of grain production.

2. Materials and methods

2.1. Site description

A field experiment was conducted at the Agricultural Experimental Site of the Scientific Observation Station of Environment at Langfang, Hebei Province, China (39°06′ N, 116°06′ E), in 2012 and 2013. The area has warm-temperate continental monsoon climate characteristics. The mean annual temperature is 12.0 °C, annual sunshine is 2660 h, and the frost-free period is 183 days. The mean annual precipitation is 556.2 mm, of which more than 70% falls during June–September. The site has a sandy loam soil [19] with the following properties (0–20 cm top layer): 13.8 g kg^{-1} organic matter, 1.1 g kg^{-1} total nitrogen (N), 75.0 mg kg^{-1} available N, 140.6 mg kg^{-1} available potassium (K), and 40.8 mg kg^{-1} available phosphorus (P).

2.2. Experimental design and field management

A spring maize hybrid (ZD958) was used. The experiments used a split-plot design, in which the main plot was tillage method, including ST (to 35 cm depth before sowing) and rotary tillage (RT, to 15 cm depth). The split plot included maize straw mulching at rates of 0% (0C), 50% (50C), and 100% chopped straw mulching (100C), and 0% (0P), 50% (50P), and 100% prostrate whole straw mulching (100P). The average maize stover yield was 8420 kg ha^{-1}, so that 50% and 100% straw coverage represent 4210 and 8420 kg ha^{-1}, respectively. Maize was the previous crop. Maize seeds were planted in narrow (40 cm) and wide rows (80 cm) with maize straw mulching before sowing (Fig. 1). Maize straw was chopped with a multi-function mill (Yulong SG40 type, Yulong Machinery Co., Ltd., Zhangqiu, Shandong Province, China) before being evenly spread in wide rows. Prostrate whole maize straw was manually cut from the maize stalk base and then spread in wide rows. ST and RT were performed in narrow rows in the spring, without incorporation of stubble or main roots into the soil.

The planting density was 82,500 plants ha^{-1}. The experiment was a randomized block design with three replicates and 24 m^2 experimental plots. N fertilizer at 225 kg ha^{-1} was applied in a split ratio of 1:2 before sowing and at 12-leaf stage (with visible leaf collars). Total phosphorus and potassium fertilizers were applied before sowing at 173 kg ha^{-1} P_2O_5 and 150 kg ha^{-1} K_2O. Maize was sown on May 11 and May 2 and harvested on September 13 and September 3 in 2012 and 2013, respectively. Herbicide application (42% propisochlor + atrazine, suspension) and manual weeding were performed during the growth period.

Reference evapotranspiration (ET_0) was measured by the Penman–Monteith method [20]. Daily rainfall, maximum and minimum temperatures, air humidity, wind speed, sunshine hours, and Class A pan evaporation were recorded daily at a meteorological station (HL20; Jauntering International Corporation, Tokyo, Japan) located within 100 m of the experimental field (Table 1).

2.3. Data collection

Each plot was harvested manually at maturity. Grain samples were air-dried to a uniform moisture content of 14% for yield evaluation. Soil water content from 0 to 30 cm depth in 10 cm increments was measured before sowing and after harvest using the oven-drying method, whereas soil water content at the 30–120 cm depth in 30 cm increments was measured with a neutron probe (NMM 503 DR; Campbell Pacific Nuclear International Inc., Concord, CA, USA). The locations of soil augering are shown in Fig. 1.

The total actual evapotranspiration over the whole growing season (ET_c, in mm), the amount of infiltration (Dw), and WUE were calculated as follows:

$$ET_c = Pe + I + S – Dw \quad (1)$$

$$Dw = 0.1 \times Pe \quad (2)$$ [21]

$$WUE = Y/ET_c \quad (3)$$ [22]

where Pe is the effective precipitation (mm) measured at the meteorological station, I is the irrigation quota (0 mm), ΔS is the change in soil water stored in the 0–120 cm soil layer (mm) before sowing and after harvest, and Y is grain yield (kg ha^{-1}). When a single rainfall event is greater than or equal to 40 mm, the soil will permit deep infiltration.

2.4. Statistical evaluation

Yield, water consumption, and WUE were determined for each plot and analyzed with the analysis of variance (ANOVA) procedure of SPSS 13.0 (SPSS Inc., Chicago, IL, USA). Comparisons among different treatments were performed with Duncan's

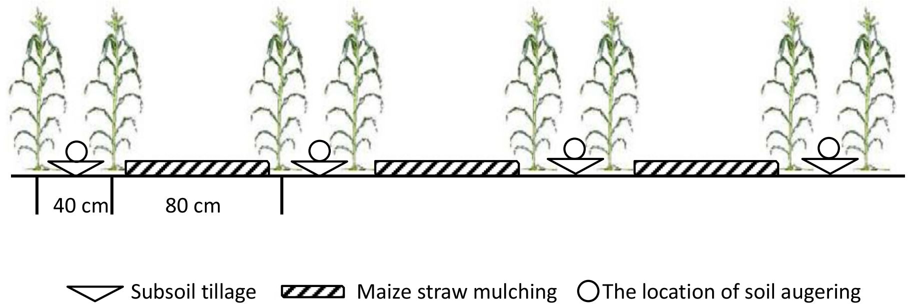

Fig. 1 – Field layout of rows for maize sowing, subsoil tillage, maize straw mulching, and soil augering.

multiple-range test. The contributions (Eta^2) of tillage and maize straw mulching to maize yield, water consumption, and WUE were calculated using a general linear model.

3. Results

3.1. *Yield response*

Maize yields in ST were higher than those in RT, and the differences were 644.5 kg ha^{-1} in 2012 and 673.9 kg ha^{-1} in 2013. Chopped straw mulching increased yield by 233.9 and 381.8 kg ha^{-1} over prostrate whole straw mulching in 2012 and 2013, respectively (Table 2). Maize with 50C showed a yield advantage. Compared to 100C, 100P, 50P, and 0, 50C yield was superior by 797.3, 559.5, 705.5, and 516.3 kg ha^{-1}, respectively, in 2012, and 836.8, 734.3, 866.0, and 738.3 kg ha^{-1}, respectively, in 2013. Over 2 years, the yield was significantly affected by tillage and maize straw mulching, but the contribution of tillage was greater than that of maize straw mulching.

3.2. *Soil water content*

ST increased soil water content. Compared to RT, ST significantly increased soil water content by 2.9% and 3.0% in 2012 and 2013, respectively (Fig. 2). Chopped straw mulching under maize increased soil water content. In 2012 and 2013, compared to prostrate whole straw mulching treatments, chopped straw mulching significantly increased soil water content by 0.2% and 0.2%, respectively. Maize with 50C showed a soil water content advantage. Compared to 100P, 100C, 50P, and 0 treatments, the 50C treatment soil moisture content increased by 3.3%, 6.6%, 9.6%, and 14.5% in 2012 and by 2.7%, 6.5%, 9.4%, and 15.2% in 2013, respectively. Over 2 years, soil water content was significantly affected by tillage and maize straw mulching, but the contribution to volumetric soil water content of straw mulching (0.917) was larger than that of tillage (0.425).

3.3. *Water consumption*

Subsoil tillage required less water consumption (Table 2) than RT. ST significantly reduced water consumption by 6.3% and 7.8% in 2012 and 2013, respectively. Maize with chopped straw mulching required less water consumption than prostrate whole straw mulching in 2012 and 2013. Compared to prostrate whole straw mulching, chopped straw mulching reduced water consumption by 1.2% in 2012 and 1.1% in 2013. Maize with 50C required less water. Compared to 100P, 100C, 50P, and 0 treatments, the water consumption of the 50C treatments was reduced by 6.1%, 17.3%, 24.6%, and 33.2%, respectively, in 2012, and by 7.0%, 18.5%, 22.7%, and 31.9%, respectively, in 2013. Over 2 years, water consumption was significantly affected by tillage and maize straw mulching, but the contribution of straw mulching to water consumption was higher than that of tillage.

3.4. *Water use efficiency*

Improved tillage and straw mulching methods can significantly improve WUE (Table 2). Our results showed that ST gave a WUE advantage. Compared to RT treatments, ST significantly increased WUE by 12.7% and 15.2% in 2012 and 2013, respectively. Chopped straw mulching gave a WUE advantage in 2012 and 2013. Compared to prostrate whole straw mulching, chopped straw mulching significantly increased WUE by 1.6% and 1.6% in 2012 and 2013, respectively. All straw mulching treatments showed higher WUE than the same treatments without straw mulching. The largest WUEs

Table 1 – Rainfall, reference evapotranspiration and evaporation at the experimental site during 2012–2013.

Month	2012			2013		
	Rainfall (mm)	ET_0 (mm)	Evaporation (mm)	Rainfall (mm)	ET_0 (mm)	Evaporation (mm)
May	6.9	122.0	91.6	6.2	113.1	59.0
June	82.6	85.6	196.9	85.6	57.8	95.9
July	256.6	49.2	50.0	230.1	44.8	47.2
August	87.5	37.5	52.2	86.1	44.6	43.4
September	129.9	46.7	22.2	121.2	40.7	24.1
Total	563.5	341.0	298.7	529.2	301.0	247.6

Table 2 – Yield, water consumption, and water use efficiency of different treatments in 2012 and 2013.

Treatment		Yield (kg ha^{-1})		Water consumption (mm)		Water use efficiency (kg ha^{-1} mm)	
		2012	2013	2012	2013	2012	2013
ST	100C	11338.0 ± 97.0 c	11162.5 ± 129.0 b	451.8 ± 15.4 g	444.4 ± 14.5 f	25.1 ± 0.7 b	25.1 ± 1.0 b
	100P	11611.0 ± 98.9.0 b	11308.0 ± 137.4 b	509.6 ± 36.8 ef	501.1 ± 14.0 e	22.9 ± 1.4 c	22.6 ± 0.5 c
	50C	12203.0 ± 162.1.0 a	12109.5 ± 117.1 a	427.7 ± 14.1 g	419.4 ± 14.1 f	28.6 ± 1.3 a	28.9 ± 1.0 a
	50P	11478.0 ± 101.7 bc	11201.0 ± 135.0 b	560.4 ± 33.2 cd	536.2 ± 32.6 d	20.5 ± 1.1 d	20.9 ± 1.1 d
	0	11664.0 ± 114.9 b	11356.0 ± 90.3 b	617.6 ± 21.6 b	597.2 ± 12.8 b	18.9 ± 0.6 de	19.0 ± 0.6 e
RT	100C	10772.0 ± 144.3 d	10615.0 ± 129.4 c	477.0 ± 6.1 fg	480.9 ± 21.6 e	22.6 ± 0.5 c	22.1 ± 1.0 cd
	100P	10974.5 ± 106.2 d	10674.5 ± 109.0 c	544.9 ± 27.6 de	555.2 ± 15.3 cd	20.2 ± 0.8 d	19.2 ± 0.6 e
	50C	11501.5 ± 143.3 bc	11341.5 ± 98.1 b	444.6 ± 21.1 g	441.3 ± 16.8 f	25.9 ± 0.9 b	25.7 ± 0.8 b
	50P	10815.5 ± 174.9 d	10518.0 ± 131.3 c	596.6 ± 33.7 bc	577.0 ± 26.8 bc	18.2 ± 0.9 e	18.2 ± 0.6 e
	0	11008.0 ± 136.1 d	10618.5 ± 106.9 c	688.3 ± 44.7 a	667.6 ± 22.8 a	16.0 ± 1.0 f	15.9 ± 0.7 f
Eta^2 (tillage)		0.901	0.923	0.397	0.649	0.734	0.841
Eta^2 (straw)		0.871	0.916	0.922	0.949	0.949	0.963

ST: subsoil tillage; RT: rotary tillage; Eta^2 (tillage): contribution of tillage; and Eta^2 (straw): contribution of maize straw mulching. 0C, 50C, and 100C refer to 0%, 50%, and 100% chopped maize straw mulching, respectively; 0P, 50P, and 100P refer to 0%, 50%, and 100% prostrate whole straw mulching, respectively.

were observed in 50C and were 14.1–15.7% higher than those in 100P, 26.5–30.6% higher than those in 100C, and 39.6–40.6% higher than those in 50P. The results over 2 years showed that WUE was significantly affected by both tillage and maize straw mulching, but that straw mulching made a larger contribution than tillage.

4. Discussion

Compared to RT, ST significantly ($P < 0.05$) increased yield and soil water content (Fig. 2), decreased water consumption, and increased WUE in spring maize over 2 years (Table 2). How can ST save water without reducing grain yield? Compared to RT, ST can break the soil plow pan to effectively alleviate soil compaction, promote water infiltration into the deep soil, and promote root penetration to absorb soil moisture [13,23]. These actions in turn indirectly improve plant water status, chlorophyll content, gas exchange, photosynthesis, and yield [8,14]. ST takes advantage of these physiological responses to decrease water consumption and increase yield and WUE.

In the present study, compared to prostrate whole straw mulching treatments, chopped straw mulching significantly ($P < 0.05$) increased yield and soil water content, decreased water consumption, and improved WUE in spring maize over 2 years (Table 2; Fig. 2). Straw mulching over a more uniform area above the soil surface and conserving soil moisture by decreasing the evaporation of soil moisture and slowing air convection on the soil surface [22,24]. Non-uniform straw mulching will cause physical obstructions at emergence,

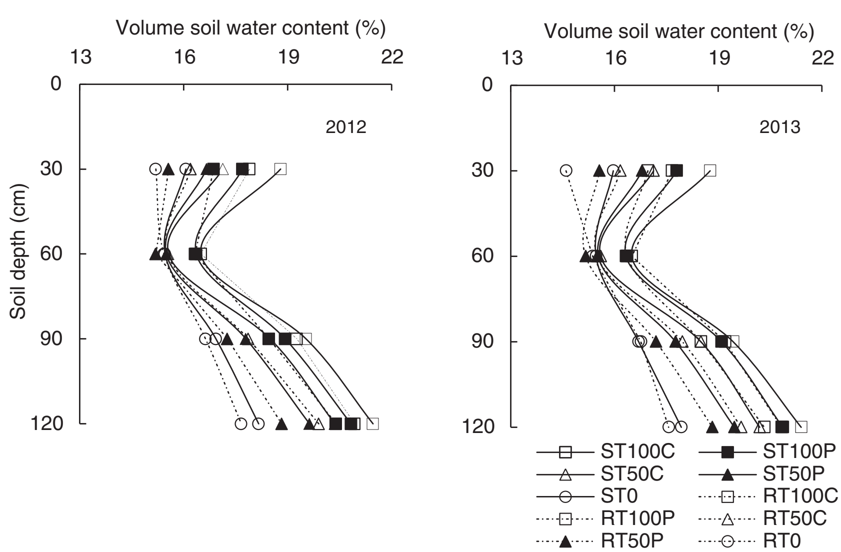

Fig. 2 – Spatial variation in soil water content at 0–120 cm during the whole growth period in different treatments in 2012 and 2013. ST: subsoil tillage; RT: rotary tillage. 0C, 50C, and 100C refer to 0%, 50%, and 100% chopped maize straw mulching, respectively; 0P, 50P, and 100P refer to 0%, 50%, and 100% prostrate whole maize straw mulching, respectively.

affecting seedling uniformity and quantity, leading to decreased yield [14,25,26]. Seedlings were more vigorous with chopped straw mulching than with prostrate whole straw mulching [27]. Uniform straw mulching on the soil surface reduces evaporation, increases soil moisture content, and decreases water consumption, saving water without reducing grain yield and leading to a higher WUE [4,14,15]. Our results also showed that, compared to 100P, 100C, 50P, and 0 treatments, 50% chopped straw mulching gave the highest WUE and the highest yield in spring maize over 2 years (Table 2). Treatments 100P, 100C, and 50P may be the result of excessive physical obstruction at emergence and of low soil temperature, leading to poor seedling quality and limited yield [27]. The amount of straw in the 100% straw mulching treatment may have been excessive.

We observed differences in the contributions of tillage and maize straw mulching to maize yield, water consumption, and WUE (Table 2). With respect to maize yield, tillage contributed more than mulching. However, with respect to soil water content, water consumption, and WUE, mulching contributed more than tillage in both years. The effects of tillage reduced compaction, permeability, porosity, and bulk density, thereby promoting root-absorbing soil water and nutrients to promote grain production with no physical obstruction at emergence [13,23,27]. Maize straw mulching reduces air convection at the soil surface, decreasing evaporation and conserving soil moisture, but increases physical obstruction at emergence, decreasing yield [15,22,24].

In conclusion, the spring maize system with ST and 50% chopped straw mulching has great potential for improving yield and WUE in the northern Huang–Huai–Hai valley, where drought seriously affects the stability of grain production.

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