https://doi.org/10.17221/96/2018-PSE

Wheat straw mulching with fertilizer nitrogen: An approach for improving soil water storage and maize crop productivity

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ABSTRACT

Akhtar K., Wang W.Y., Khan A., Ren G.X., Afridi M.Z., Feng Y.Z., Yang G.H. (2018): Wheat straw mulching with fertilizer nitrogen: An approach for improving soil water storage and maize crop productivity. Plant Soil Environ., 64: 330–337.

Field studies using wheat straw mulching effects on soil water storage and maize development were conducted in China. The studies contained four treatments during three years (2014–2016): CK (no straw and no nitrogen); N (no straw mulching with 172 kg N/ha); HS + N (half straw mulching at the rate of 2500 kg/ha with 172 kg N/ha), and FS + N (full straw mulching at the rate of 5000 kg/ha with 172 kg N/ha). The FS + N treatment significantly increased soil water storage in a drought period during crop growth stages and promoted plant growth along with increased evapotranspiration. The FS + N treatment increased the soil water storage (26.5, 19.9 and 11.1 mm), grain yield (28.7, 6.93 and 2.4%), and water use efficiency (26.6, 6.64 and 2.40%) compared to CK, N and HS + N, respectively. In conclusion, compared to N, HS + N or FS + N increased the biomass (11 and 19%) and water use efficiency (4 and 5%), respectively, and are considered beneficial in Guanzhong, China. Mulching levels were superior to N and compensated the wheat nitrogen requirements. Thus, further studies with minimum fertilizer nitrogen for an environmentally friendly and effective approach are recommended in semiarid regions of China.

Keywords: semi-arid region; *Zea mays* L.; rainfall; soil temperature; crop yield

Decreased crop productivity in arid and semi-arid regions is due to water shortage (Tavakkoli and Oweis 2004) and thus water availability is important for the stability of grain yield. Crop productivity is affected by variations in soil water storage (Liu et al. 2010). The increase in soil water storage is possible with addition of straw mulch as a surface mulching material, which increases the soil water content, water use efficiency (WUE), and crop production (Wang et al. 2012). Soil water storage was improved about 30 mm with the use of straw mulch at the rate of 6000 kg/ha (Liu et al. 2010). Similarly during the maize growing season, 106.9 mm soil water was stored in 0–200 cm soil depth with the use of straw mulch (Li et al. 2013).

Generally, the addition of residues such as straw mulching increases the grain yield (Wang et al. 2012); however, Gao and Li (2005) observed that winter wheat yield decreased with the use of straw mulch. It was also noted that straw mulching increased soil moisture content and nutrient storage in the maize-wheat cropping system in the northwestern regions of India, and thus enhanced the soil fertility and crop productivity (Sharma et al. 2010). Similarly, addition of *Pueraria* residues to the soil increased maize yield by 37% with burning or by

Supported by the Shaanxi Provincial Government of China, Project No. 2016KTCL02-11.

47% with mulching (Kolawole et al. 2004). Such controversy led us to understand the responses of soil water storage and crop production under straw mulching. Recently, it has been reported that about 90% of harvested wheat residues in northern China is used as mulch (Fang et al. 2011), and thus it would be very useful to understand its effects on plant growth and soil properties (Govaerts et al. 2007).

The limitation of water resources is the major constraint for crop production (Rockström et al. 2007). In future, declining precipitation will reduce the yield of crops, and will pose a serious threat to food security in semi-arid regions (Lobell et al. 2008). Keeping in view the importance of mulching and limited documentation of mulching effects on water storage, WUE and maize production in semi-arid regions of China, this study was planned with core points of (1) to explain the responses of soil water storage, water use efficiency and yield of summer maize to mulching and nitrogen treatments, and (2) to quantify the most suitable amount of straw mulching for semiarid region of China.

MATERIAL AND METHODS

Site description. The experimental site (108°07'E, 34°12'N) is situated within Northwest A&F University, China, Yangling, Shaanxi province. The area is located 520 m a.s.l., with negligible slope (~ 0.4%) representing a flat surface. Mean annual temperature and precipitation are 12.9°C and 660 mm, respectively. The precipitation is mainly concentrated in July to September. The temperature and rainfall data collected in the experimental site between 2014–2016 are given in Figure 1. The soil is classified as Lou soil, belonging to the anthrosol category, having silt clay loam soil texture, soil water storage of 125 mm, saturated soil water content of 40%, pH 8.3 and field capacity of 22.4% in 0–100 cm soil depth. The contents of soil organic carbon, available N, P, K, and total N and P were 11.2 g/kg, 26.5 mg/kg, 5.1 mg/kg, 132 mg/kg, 0.52 g/kg and 0.49 g/kg, respectively, measured according to Bao (2005) in 0–40 cm soil depth at the start of the experiment in 2011. The mulching treatments (mentioned below) were imposed as a part of this original experiment since 2010 and had a continuous maize-wheat crop rotation. In 2014–2016, these treatments were re-established to quantify the effects of wheat straw mulching on soil water storage, water use efficiency and maize crop productivity at the experimental area of Northwest A&F University, Shaanxi province, China.

Experimental design and field management. The experimental treatments: CK (no straw and no nitrogen); N (no straw mulching with 172 kg N/ha); HS + N (half straw mulching at the rate of 2500 kg/ha with 172 kg N/ha); FS + N (full straw mulching at the rate of 5000 kg/ha with 172 kg N/ha) were arranged in a randomized complete block design with four replicates in plot size of 8 m length by 8.25 m width (66 m^2). The wheat crop was harvested every year at the end of May; the straw was chopped into 3–5 cm and was used as a mulching material for the next maize crop

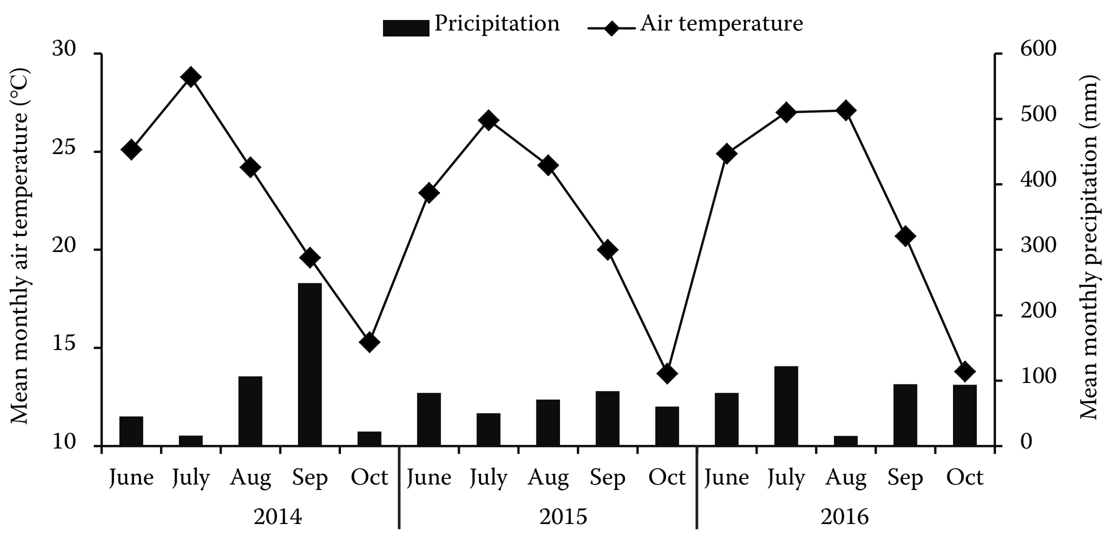

Figure 1. Mean monthly precipitation and air temperature between June 2014 and October 2016

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during 2014–2016 in the same plots of the field. Additionally, urea fertilization was applied equally to all plots except control at the rate of 172 kg N/ha in the jointing stage. The summer maize (cv. Luo dan No. 9) was planted at a seed rate of 60 kg/ha on 15 June 2014, 15 June 2015, 14 June 2016, using a machine and a depth-controlling wheel with a row spacing of 75 cm and 25 cm space maintained between plants. No ploughing was made in any year (2014–2016) before sowing of the maize seed. Each year, manual weeding was conducted as required during the field experiment. Every year, in the mid of July, a total of 120 mm irrigation water was applied to the experimental field in addition to rainfall (Figure 1).

Calculations and measurements. The soil water contents in 0–100 cm soil depth (with interval of 10 cm) were measured in three places taken randomly in each plot. The collected soil samples were oven-dried at 105°C for 24 h during each growth stage of maize crop for the entire duration of the project (2014–2016). The soil water storage was calculated using Eq. 1 (Liu et al. 2014b):

$$SW = \sum_{i}^{n} h_i \times \rho_i \times b_i \times 10/100 \quad (1)$$

Where: SW (mm) – average soil water storage (0–100 cm); h_i (cm) – soil layer depth; ρ_i (g/cm^3) – soil bulk density in each different soil layer; b_i – percentage of soil moisture by weight; n – number of soil layers; i = 10, 20, 40, . . . 100.

The evapotranspiration (ET) was calculated by the change in soil water storage between sowing and harvesting stage at the depth of 0–100 cm (Zhao et al. 2014) using Eq. 2:

$$ET = \Delta SWS + P + I \quad (2)$$

Where: ET – evapotranspiration (mm); ΔSWS (mm) – change in soil water storage between sowing and harvesting stage; P – precipitation amount (mm); I – irrigation amount (mm).

The water use efficiency (WUE) was calculated using Eq. 3 (Zhou et al. 2011b):

$$WUE = \frac{Y}{ET} \quad (3)$$

Where: Y – grain yield (kg/ha); ET – total evapotranspiration (mm). The soil surface temperature in 0–20 cm soil depth was measured using a square thermometer buried in the middle of crop rows during the whole growing season in 2014–2016; the data were recorded with the interval of 25 days after sowing (DAS).

Maize total dry matter (i.e. above (shoots) and below ground (roots) parts) of fifteen representative plants taken randomly in each plot were measured throughout the growing periods with the interval of 25 DAS. Plants samples were dried in an oven at 65°C until constant weight. The grain and biomass yield were recorded in the two central rows at harvest maturity, air dried in all the three years (2014–2016). Similarly, all plants in the two central rows at harvest maturity were counted and converted into plant/ha, accordingly. The profitability of the mulching material was worked out considering the crop income, and all expenditure incurred during the project. The output to input (O/I) ratio was worked out for comparison.

Statistical analysis. For each variable, the mean values were calculated and for the comparison of different treatments, analysis of variance (ANOVA) was used. The means were compared by the least significant difference (*LSD*) test. The statistical analyses were performed using the SPSS 20.0 (SPSS Inc., Chicago, USA). The original Pro software (Northampton, UK)was used to generate figures.

RESULTS AND DISCUSSION

Soil water storage was the greatest at 50 days after sowing (DAS) during 2015 and 2016; however, the increase in soil water storage was higher at 100 and 120 DAS in 2014 due to more rainfall during this stage (Figure 2). The non-uniform distribution of seasonal rainfall had a strong impact on maize crop production in Guanzhong, China (Blanco-Moure et al. 2012). Thus, compensating the plants' water demand during drought period from mulching seems to be very beneficial. During 2014, the soil water storage at harvest was significantly ($P < 0.05$) higher compared to the soil water storage at the sowing stage. This increase in water storage was caused by sudden high rainfall (249.1 mm) during the growing period in 2014. The three-year average soil water storage under FS + N treatment was increased by 4.6, 10.8 and 15.8% compared with HS + N, N and CK, respectively. The shortage of water in arid and semi-arid regions is a major problem causing limited crop production (Tavakkoli and Oweis 2004). The straw mulching provides a covering layer on the soil surface and saves rain water by reducing the runoff of rain water thus conserving more water and increasing the soil water storage (Yang and Guo 1994,

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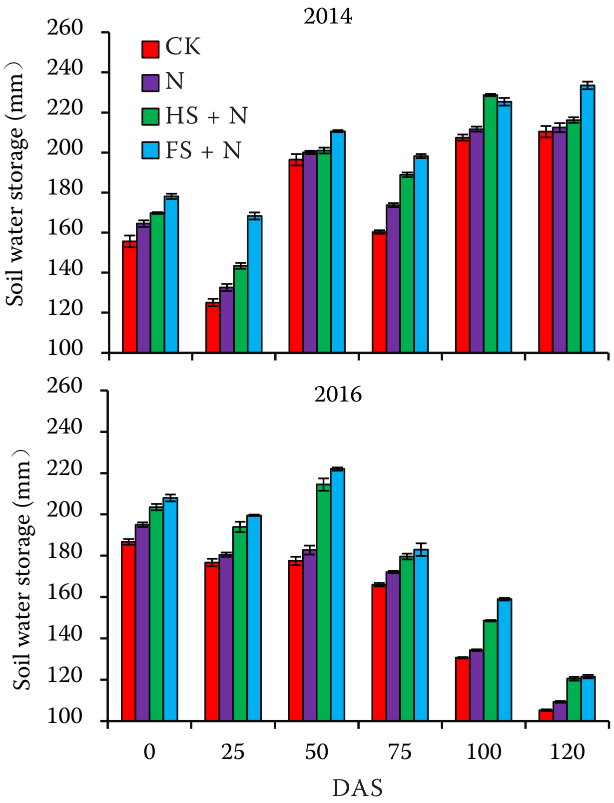

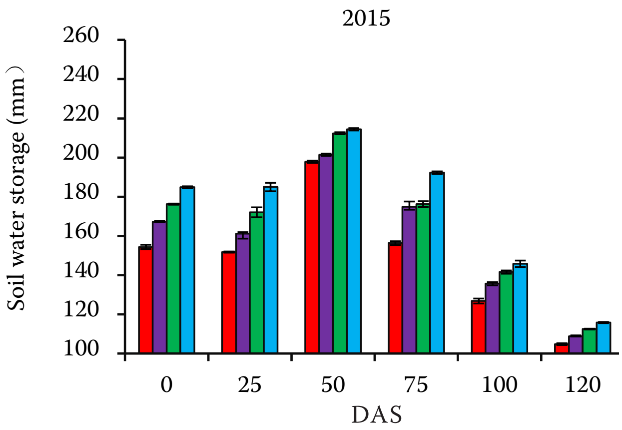

Figure 2. Variations in soil water storage during the growing season of maize. CK – no straw mulching and no nitrogen; N – no straw mulching and 172 kg N/ha; HS + N – half straw mulching at a rate of 2500 kg/ha of wheat straw with 172 kg N/ha; FS + N – full straw at a rate of 5000 kg/ha of wheat straw with 172 kg N/ha

Deng et al. 2006, Qin et al. 2013). The present study indicated that surface FS + N regime conserves higher soil moisture across the growing season principally during early growth stages compared with CK. The surface application of mulching acts as a physical barrier for reducing evaporation losses, reduces rainfall water runoff and thus increases water storage and slows down air convection on the soil surface (Kang et al. 2004, Fan et al. 2013). Furthermore, the FS + N regime enhanced soil water storage, so that

Table 1. Maize plant population, biomass and grain yield, evapotranspiration (ET), and water use efficiency (WUE) under different treatments

	Treatment	Number of plants/ha	Biomass yield (kg/ha)	Grain yield (kg/ha)	ET (mm)	WUE (kg/ha/mm)
2014	CK	46 667^{c}	13 823^{d}	7837^{d}	483^{b}	16.2^{d}
	N	50 000^{bc}	16 067^{c}	9338^{c}	489^{a}	19.1^{c}
	HS + N	56 667^{ab}	17 207^{b}	9700^{b}	491^{a}	19.8^{b}
	FS + N	60 667^{a}	18 867^{a}	9971^{a}	482^{b}	20.7^{a}
2015	CK	50 000^{b}	13 657^{d}	7275^{d}	457^{d}	15.9^{d}
	N	60 000^{a}	15 553^{c}	8763^{c}	465^{c}	18.8^{c}
	HS + N	60 333^{a}	16 010^{b}	9208^{b}	471^{b}	19.6^{b}
	FS + N	63 333^{a}	16 927^{a}	9424^{a}	476^{a}	19.8^{a}
2016	CK	54 667^{b}	13 883^{d}	7295^{c}	470^{c}	15.5^{c}
	N	60 000^{ab}	15 337^{c}	8866^{b}	474^{bc}	18.7^{b}
	HS + N	63 333^{a}	18 930^{b}	9257^{a}	471^{ab}	19.6^{a}
	FS + N	66 667^{a}	20 217^{a}	9442^{a}	475^{a}	19.9^{a}

CK – no straw mulching and no nitrogen; N – no straw mulching and 172 kg N/ha; HS + N – half straw mulching at a rate of 2500 kg/ha of wheat straw with 172 kg N/ha; FS + N – full straw at a rate of 5000 kg/ha of wheat straw with 172 kg N/ha. Values within a column for the same year followed by different letters are significantly different ($P < 0.05$)

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Table 2. Dry biomass (g/plant) under different treatments

	Treatment	25 DAS	50 DAS	75 DAS	100 DAS	120 DAS
2014	CK	1.7^{c}	3.1^{c}	51.9^{c}	190.7^{d}	195.4^{d}
	N	1.8^{c}	10.9^{b}	70.1^{c}	250.7^{c}	291.5^{c}
	HS + N	2.9^{b}	15.0^{b}	216.4^{b}	443.2^{b}	487.5^{b}
	FS + N	4.4^{a}	29.3^{a}	258.6^{a}	492.9^{a}	542.2^{a}
2015	CK	2.2^{c}	4.9^{d}	53.5^{d}	155.1^{c}	166.2^{c}
	N	2.4^{c}	15.3^{c}	100.4^{c}	223.1^{b}	335.1^{b}
	HS + N	6.5^{b}	26.0^{b}	190.6^{b}	287.3^{a}	418.7^{ab}
	FS + N	9.6^{a}	39.6^{a}	220.8^{a}	323.1^{a}	484.7^{a}
2016	CK	1.9^{d}	4.9^{d}	41.5^{c}	153.4^{d}	184.1^{d}
	N	3.1^{c}	21.6^{c}	59.5^{c}	245.6^{c}	368.3^{c}
	HS + N	8.1^{b}	28.8^{b}	175.4^{b}	395.3^{b}	411.4^{b}
	FS + N	10.5^{a}	40.7^{a}	203.8^{a}	433.0^{a}	476.3^{a}

DAS – days after sowing; CK – no straw mulching and no nitrogen; N – no straw mulching and 172 kg N/ha; HS + N – half straw mulching at a rate of 2500 kg/ha of wheat straw with 172 kg N/ha; FS + N – full straw at a rate of 5000 kg/ha of wheat straw with 172 kg N/ha. Values within a column for the same year followed by different letters are significantly different ($P < 0.05$)

the ET level under FS + N treatments was increased by 1.7% compared with CK (Table 1). The efficient utilization of the precipitation is achieved through reducing evaporation and increasing transpiration. That is why a major concern for scientists is the loss of significant amounts of soil water in dryland areas as a result of evaporation (Cooper et al. 1987, Perry 1987).

Lower water storage during early phases (25 and 50 DAS) of the crop growth was observed in 2014 than 2015 or 2016. This low soil water storage in 2014 resulted in low dry matter (shoot + root) at 25 and 50 DAS as compared to the dry matter (shoot + root) accumulated at 75, 100 and 120 DAS (Table 2). These decreases in dry matter were comparatively lower in HS + N or FS + N than in N treatment. This improvement in dry matter in mulching treatments might be associated with greater water storage and decreased soil temperature (Li et al. 2001, Qiang et al. 2008) and thereby significantly increased total plant dry matter during the crop growth stages (Duan et al. 2006). Similar results for increased dry matter with biodegradable film mulching (Wang et al. 2007) or residue management (Khan et al. 2018) were documented in literature. The total dry matter at each stage of maize growth was significantly ($P < 0.05$) increased under FS + N treatment compared with HS + N, N and CK in 2014, 2015 and 2016. At harvest (120 DAS), the total dry matter with FS + N regime was by 61.9, 169.4 and 319.2 g/plant higher than HS + N, N and CK, respectively (Table 2) over three years. The increase in dry matter is due to the positive impact of mulching on growth and development of maize (Liu et al. 2014a). The average increase in dry matter was 7.4, 19.3 and 35.4% by FS + N treatment compared with HS + N, N, and CK, respectively, over three years. The number of maize plants/ha was higher at FS + N (Table 1) compared with CK, which might be due to higher water storage and favourable conditions for plant emergence. The dry spell during the early stage of 2014 resulted in lesser plants in CK and N treatments as compared with FS + N. Therefore, our results authenticated the findings of Stagnari et al. (2014), who observed higher number of plants and total biomass yield with increased straw mulching. Likewise, Chen et al. (2004) documented that straw mulching decreased soil temperature and increase soil water storage, and thereby improved maize growth.

The grain yield and water use efficiency of FS + N treatment were significantly ($P < 0.05$) higher than that of HS + N, N and CK in 2014–2016 (Table 1). The three years (2014–2016) average grain yield (28.7, 25.7 and 20.3%) and water use efficiency (26.6, 23.6 and 18.7%) was significantly increased by FS + N, HS + N and N treatments, respectively, compared with CK. A significant increase in the grain yield and WUE is because of high soil water storage. The soil water contents indirectly improve biomass and yield of crops, and increase water

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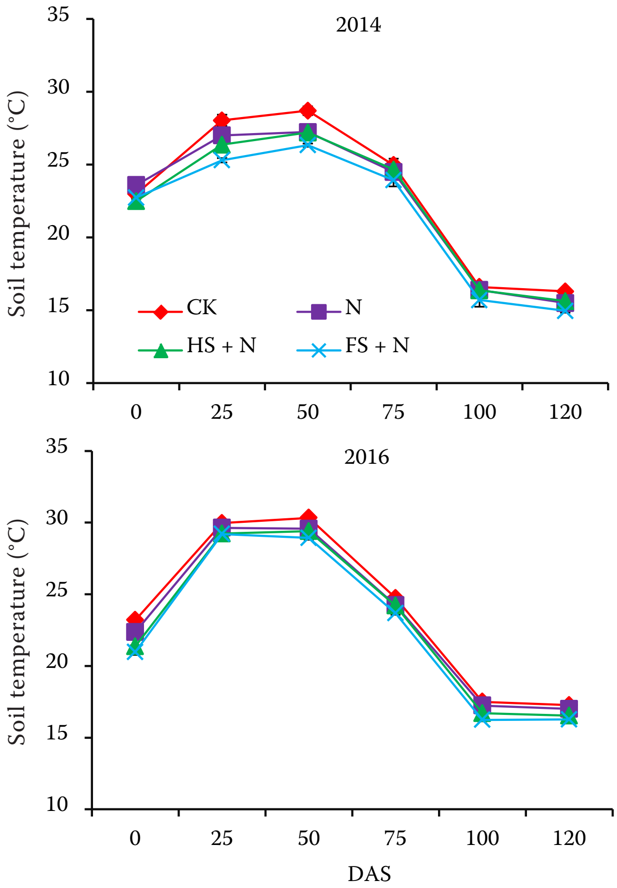

Figure 3. Soil temperature in the 0–20 cm layer during the growing season of maize. DAS – days after sowing; CK – no straw mulching and no nitrogen; N – no straw mulching and 172 kg N/ha; HS + N – half straw mulching at a rate of 2500 kg/ha of wheat straw with 172 kg N/ha; FS + N – full straw at a rate of 5000 kg/ha wheat straw with 172 kg N/ha. The vertical bars represent the standard error of the mean

use efficiency (Wang et al. 2012, Tao et al. 2013). Thereby, sufficient supply of water is beneficial for growth and yield of winter wheat (Zhou et al. 2009, 2011a) and soil water during the wheat growing season contributed up to 43% in wheat yield (Li and Shu 1991). Similarly, Tao et al. (2015)

Table 3. Economic benefits (USD/ha) under different treatments

Treatment		SI	FI	LI	TI	TO	NI	O/I
2014	CK	192	0	1136	1328	2113	785	1.6
	N	192	96	1136	1424	2518	1094	1.8
	HS + N	192	96	1056	1344	2615	1271	1.9
	FS + N	192	96	976	1264	2688	1424	2.1
2015	CK	196	0	1160	1356	1843	487	1.4
	N	196	98	1160	1454	2220	766	1.5
	HS + N	196	98	1078	1373	2333	961	1.7
	FS + N	196	98	997	1291	2388	1097	1.8
2016	CK	191	0	1079	1271	1797	526	1.4
	N	191	91	1079	1362	2183	822	1.6
	HS + N	191	91	1003	1286	2280	994	1.8
	FS + N	191	91	927	1210	2325	1116	1.9

CK – no straw mulching and no nitrogen; N – no straw mulching and 172 kg N/ha; HS + N – half straw mulching at a rate of 2500 kg/ha of wheat straw with 172 kg N/ha; FS + N – full straw at a rate of 5000 kg/ha wheat straw with 172 kg N/ha; SI – seed input; FI – fertilizer input; LI – labour input (including cost of straw removal, thinning, weeding, sowing and harvesting); TI – total input (SI + FI + LI); TO – total output; NI – net income; O/I – output:input ratio – TO/TI

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testified that a significant improvement in grain yield with decreased water consumption improved WUE in maize. Researchers (Liu et al. 2009, Bu et al. 2013) reported that soil moisture and temperature are important factors that affect crop growth and development in semi-arid areas. During the whole growing cycle, 24.3°C was the average air temperature. This increase in soil temperature (Figure 3) in CK retained less soil water during the vegetative stage of maize noticeably in 10–50 DAS, and thus reduced the growth and development of maize as compared to the accumulated biomass in the mulching treatment. Additionally, rainwater was retained by FS + N treatment during the growth period of maize causing less heat absorbed by the soil, and thus enhanced the yield compared to CK. Similarly, the results indicated that in the CK treatment, the excessive physical barrier at emergence, high soil temperature along with less water storage led to poor seedling and limited yield of maize. These results are in consistence with Li et al. (2014). Mulching increased the grain yields and economic benefits compared with CK. The FS + N regime of mulching had positive effects and led to the highest net income (1212 USD/ha), output/input ratio (2.0) than the rest of treatments (Table 3).

In the current study, FS + N treatment significantly increased soil water storage, and thus it is suggested that FS + N is beneficial to be used for storing more rainwater and reducing water scarcity in the drought period and subsequently increases the crop yield. These outcomes also indicated that farmers can implement the usage of straw mulching with nitrogen to achieve the optimum crop yield and water use efficiency in Guanzhong, China.

Acknowledgements

We are thankful to all co-authors for their full time support during the experiment and manuscript revision. We are also thankful to the anonymous reviewers and the editor of Plant, Soil and Environment for their constructive suggestions and comments.

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Received on February 11, 2018
Accepted on May 30, 2018
Published online on June 12, 2018