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Research Paper

Effects of plastic film mulching on rainfall storage and water use in forage maize fields in the cold and arid areas of Northern China

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ABSTRACT

An experiment was carried out in 2016-2017 at the Zhangbei agricultural resource and ecological environment key field research station, Ministry of Agriculture and Rural Affairs of the P.R.C. in order to explore the way of stable and high yield of forage maize under the unstable time sequence and quantity of precipitation in cold arid area of Northern China. Soil water dynamics, yield and water use efficiency (WUE) in maize field were studied with 4 treatments of Flat cultivation without mulching (CK), Double ridges furrow planting cultivation with film mulching (DM), Flat cultivation with film mulching (FM) and cultivation with film mulching under soil layer (UM). The main aquifers of the meadow chestnut soil in the cold and arid areas of Northern China are 0-60 cm. The soil water storage during the growth period was significantly affected by precipitation and field water consumption. FM and DM stored the unstable precipitation in time and quantity in soil, thereby promoting water infiltration, accumulation of biomass and WUE in the early growing period of maize, increasing yield by 40.6%-67.2%, increasing WUE by 49.3%-87.5%, and their effect became more obvious in the year of abundant water. UM suppressed soil water evaporation and ensured a stable water supply, and promoted the accumulation of biomass in the mid-term growth of maize. It increased yield of forage maize by 10.6%-71.3%, increased the WUE by 17.1%-79.5%, and the effect was obvious in the dry year. DM and FM can effectively improve the rainfall storage and the WUE of maize in the rain-fed farmland in Northern China, and the UM is more suitable for the high efficiency production of farmland with rich soil water storage.

Key words: Plastic film mulching, forage maize, soil moisture, water use efficiency (WUE).

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INTRODUCTION

Located in the north of the Great Wall, the North China Plateau (NCP) belongs to the cold and semi-arid farming pastoral ecotone. This region is higher in altitude, with poor soil and dry climate, and the water resources are closed circulation (Du et al., 2005). Effective cultivation measures should be taken to promote the efficiency transformation of ineffective precipitation, improve soil water storage (SWS) (Li et al., 2013; Zhou et al., 2012), rationally regulate the water dissipation of farmland and improve WUE (Kou and Shi, 2011; Li et al., 2013a; Liu et al., 2008; Li et al., 2016), which is the key to stable and high yield of crops in the rain-fed areas. Film mulching can reduce the evaporation of soil surface, keep the early stage soil water and ensure the later stage water supply, and improve the physiological and growth characters of the crops (Huang and Zhang, 2005). The evaporation loss of the mulched radish field in the NCP cold region could be decreased by 15.5-39.2 mm and the WUE increased by 40.0%-81.7% (Huang and Zhang, 2005).

Table 1: The physical and chemical characteristics of the tested soil.

Soil tape	Depth of soil (cm)	O.M ($g•kg^{-1}$)	Total N ($g•kg^{-1}$)	Total P ($g•kg^{-1}$)	Available N ($mg•kg^{-1}$)	Available P ($mg•kg^{-1}$)	Bulk density ($g•cm^{-3}$)
Meadow chestnut soil	0～20	26.4	1.71	0.48	112.0	11.0	1.33

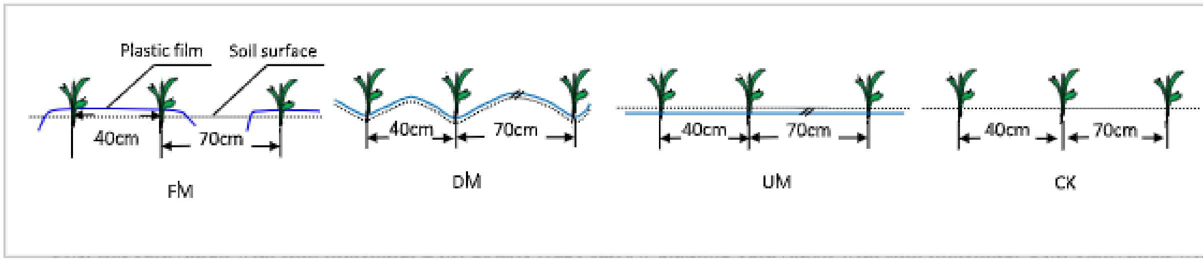

Figure 1: Schematic diagram of each test.

Mulching can prolong the functional period of maize leaves, increase photosynthetic rate, stomatal conductance and leaf WUE, and yield increased by 69.14% (Gao et al., 2012).

The film mulching in the cold region significantly promoted the absorption of nitrogen of maize, and the apparent utilization rate of nitrogen increased by 13.3% compared with the average of the cultivation without mulching (Du et al., 2007). The small area water collection planting method of ridge mulching and furrow planting can make the spring wheat grow 2-6d in advance, increase the seedling rate by 11-17.9%, and increase the water supply capacity of soil by 46.3-158.0% (Zhu et al., 2001). The double ridge furrow plating cultivation with film mulching of spring maize could convert the ineffective precipitation less than 5 mm into available water in the soil, and the WUE of maize increased by 66.43% according to the experiment conducted at Dingxi, Gansu province (Gao et al., 2012). However, the warming effect of the film mulching will promote early onset of crop and consume a large amount of soil water storage. In the middle and late period, the soil water supply is insufficient or the weather drought reduced the yield of rain-fed wheat (Li et al., 2001) and maize (Zhang et al., 2008).

In the semi-arid region of the NCP, the effects of film mulching and nitrogen application on the production and nutritional quality of the forage maize have been progressed, but the spatial and temporal effects of different film mulching methods on the storage of precipitation and the dissipation characteristics of soil moisture in farmland are still blank. In this study, the different planting methods of mulching in the forage maize field in cold and arid area northern China were studied. By comparing the temporal and spatial variation of soil moisture in the growing season, the characteristics of soil water storage and consumption, and the effect of water production under the film mulching are to be clearly defined, which provided the basis for the technological innovation of the stable and high yield of the forage maize in the region.

MATERIALS AND METHODS

The general situation of the test area

The experiment was carried out in 2016-2017 in the Zhangbei agricultural resource and ecological environment key field research station, Ministry of Agriculture and Rural Affairs of the P.R.C. The test station is located in Zhangbei County, Hebei province. The geographical coordinates are 114°42′E and 41°09′N. The main ecological environment conditions represent the semi-arid region of the NCP. The experimental station is 1420 m above sea level, with an average annual temperature of 3.9°C, 382.5 mm of rainfall, frost free period of 135d, ≥0°C accumulated temperature of 2810.6°C•d, and ≥10°C accumulative temperature of 2426.3°C•d .

The experimental soil is meadow chestnut soil. The soil types and their physicochemical properties are shown in Table 1. The annual precipitation in growth period of forage maize is about 270 mm. The annual precipitation in 2016 and 2017 was 309.8 and 222.4 mm, respectively.

Experimental design

Treatment included Flat cultivation with film mulching (FM), Double ridge furrow planting cultivation with film mulching (DM), cultivation with film mulching under soil layer (UM) and flat cultivation without mulching(CK). The design was randomized 3 times. The planting pattern of each treatment is shown in Figure 1.

The plot area of 39.6 m^2. P_2O_5 120 kg ha^{-1} and K_2O 200kg ha^{-1} were used as base fertilizer before sowing. The experimental crop was forage maize variety Xunqing 518, and the planting density was 120000 plants ha^{-1}. In 2016, the sowing and harvesting dates were on May 27 and August 26, respectively while in 2017, they were on May 24 and September 5, respectively. There was no irrigation during the whole period of the growth.

FM: After maize hill seeding, for every 2 rows as 1 band, mulching with film of 90 cm in width, the film edge was put into the ditch and compacted with soil. The micro furrow between the two belts can infiltrate precipitation. After the emergence of maize, the seedlings were let out and the seedling pores were sealed by soil.

DM: maize was planted in the furrow of 2 rows with spacing of 40 cm, mulching by film of 90 cm in width. The edges of the film were compacted with the soil at the ridge, and the film in furrow was also pressed by soil. After the emergence of maize, the seedlings were set out and the seedlings pores were sealed by soil.

UM: after maize hill seeding, every 2 rows as 1 band were covered with film of 90 cm in width; the film was evenly covered with 2 cm soil layer. The maize automatically breaks the film after germination, and the seedling pores can infiltrate the precipitation.

Measurement and method

Maize yield

Fresh weight of maize was measured in each plot at harvest. 10 samples from each plot were taken to measure fresh weight and dry weight. The dry biomass rate and the dry weight yield of each treatment were calculated. During the growing stage, the soil moisture was measured at fixed interval, and 5 samples were taken from each plot, and the maize growth traits and dry mass were measured.

Soil moisture

Soil moisture content (SMC) was determined by drying method. The soil depth was 0-100 cm, and 1 soil sample per 10 cm:

$$SMC (\%) = [WS (g) - DS (g)] / DS (g).$$

Where SMC is the soil moisture content, WS is the wet soil weight, DS is the dry soil weight.

$$SWS (mm) = \sum h_i (cm) \times p_i (g\ cm^{-3}) \times b_i (\%) \times 10/100.$$

Where SWS is the soil water storage, h_i is the soil depth, p_i is soil bulk density, b_i is the soil moisture weight percentage, i=10, 20, 30... 100.

$$ET (mm) = SWS_1 (mm) - SWS_2 (mm) + P (mm).$$

Where ET is the field water consumption, SWS_1 is the initial stage soil water storage, SWS_2 is the final soil water storage, and P is the stage precipitation.

$$WUE (kg \bullet ha^{-1} \bullet mm^{-1}) = Y/ET.$$

Where WUE is the water use efficiency, and Y is the biomass yield of forage maize ($kg \bullet ha^{-1}$).

To estimate the effect and characteristics of experimental treatment on crop water utilization, the concept of Surplus water supply (WS) was adopted.

$$WS (mm) = [Yt (kg \bullet ha^{-1}) / WUEck (kg \bullet ha^{-1} \bullet mm^{-1})] - ETck (mm).$$

Where WS is the surplus water supply, Yt is the treatment crop yield, WUEck is the control water use efficiency, and ETck is the control field water consumption.

Statistical analysis

Data were analyzed using Excel 2010 and SPSS17 data analysis system.

RESULTS AND ANALYSIS

Dynamic change of SWS in 0-100 cm soil layer

The change of SWS in each treatment of 0-100 cm was significantly affected by precipitation (Figure 2A and B). In 2016, the precipitation was abundant and its distribution was more balanced. In the period of maize growth, the SWS increased more than that of the planting time. The SWS of different treatments at each measure time showed as: DM>FM>CK>UM. The SWS of DM and FM in the whole growth period was 11.6 and 9.9% higher than that of CK. The SWS of UM was 0.9% lower than that of CK. In the early (June 25), the middle (July 27) and the later maize growth period (August 25), the SWS of FM increased by 22.1, 6.3 and 18.6 mm, respectively than CK. While for DM, it was increased by 33.1, 23.7, and 19.9 mm as compared with CK. For UM, it was 22.5 and 33.6 mm lower in the early and middle periods than that of CK, and the later period was increased to 6.8 mm than CK.

The year 2017 was a partial drought year and the distribution of precipitation was uneven. The SWS fluctuated widely around the sowing period, and the overall performance of SWS was UM > DM > FM > CK. In the early stage of maize growth before June 14, the precipitation was less and the intensity was low, the treatments showed the trend of water consumption in the soil. The SWS in CK was reduced by 20.7 mm. The SWS of FM and DM decreased by

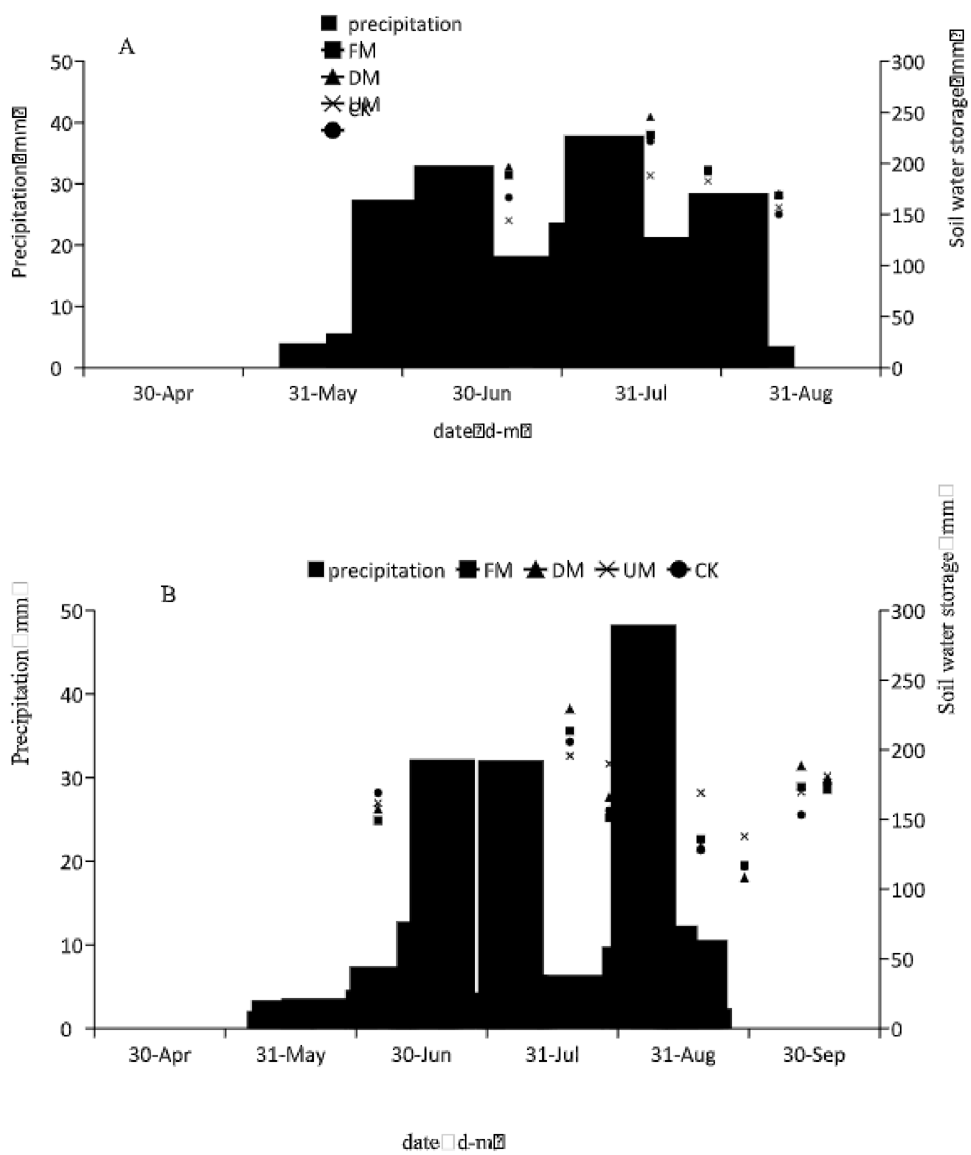

Figure 2: Dynamic changes of SWS under different mulching treatments (A 2016, B 2017).

9.3 and 18.9 mm, respectively, and in UM, it was 15.5 mm higher than that of the CK. These can be related to the strong growth of maize and high evapotranspiration in FM and DM, while in UM, it was weak, the transpiration water consumption was less and the soil surface evaporation was effectively contained.

From June 28 to July 8 of 2017, there were 4 times rainfall and the cumulative amount of precipitation was 52 mm, the SWS of each treatment increased significantly and the CK increased by 39.1 mm than that of sowing date. FM and DM had water collecting effect, and the SWS was 7.7 and 23.4 mm higher than CK, while in UM, the SWS was 10.1 mm lower than CK because of the blocking of the infiltration of precipitation. Precipitation of 7 mm occurred only once during the period of July 28 to August 17, the atmosphere drought and the maize transpiration made the soil water into the valley in August 17. The SWS was reduced by 50.3 mm in CK, and in FM, it was nearly the same as CK, while in DM, the SWS was 8.6 mm lower than CK. UM could contain soil evaporation and it was 21.3 mm higher than CK.

It was observed that the effect of precipitation collection of DM was significant in the year of abundant water, but the effect of soil evaporation containment of UM was good, especially when it was a dry year type and the soil was rich in water storage. FM had both precipitation collection and soil evaporation containment effect.

Spatial dynamic change of SMC in 0-100 cm soil layer

Taking 2017 as an example, the spatial change of SMC in 0-100 cm soil layer was analyzed (Figure 3). The main factors

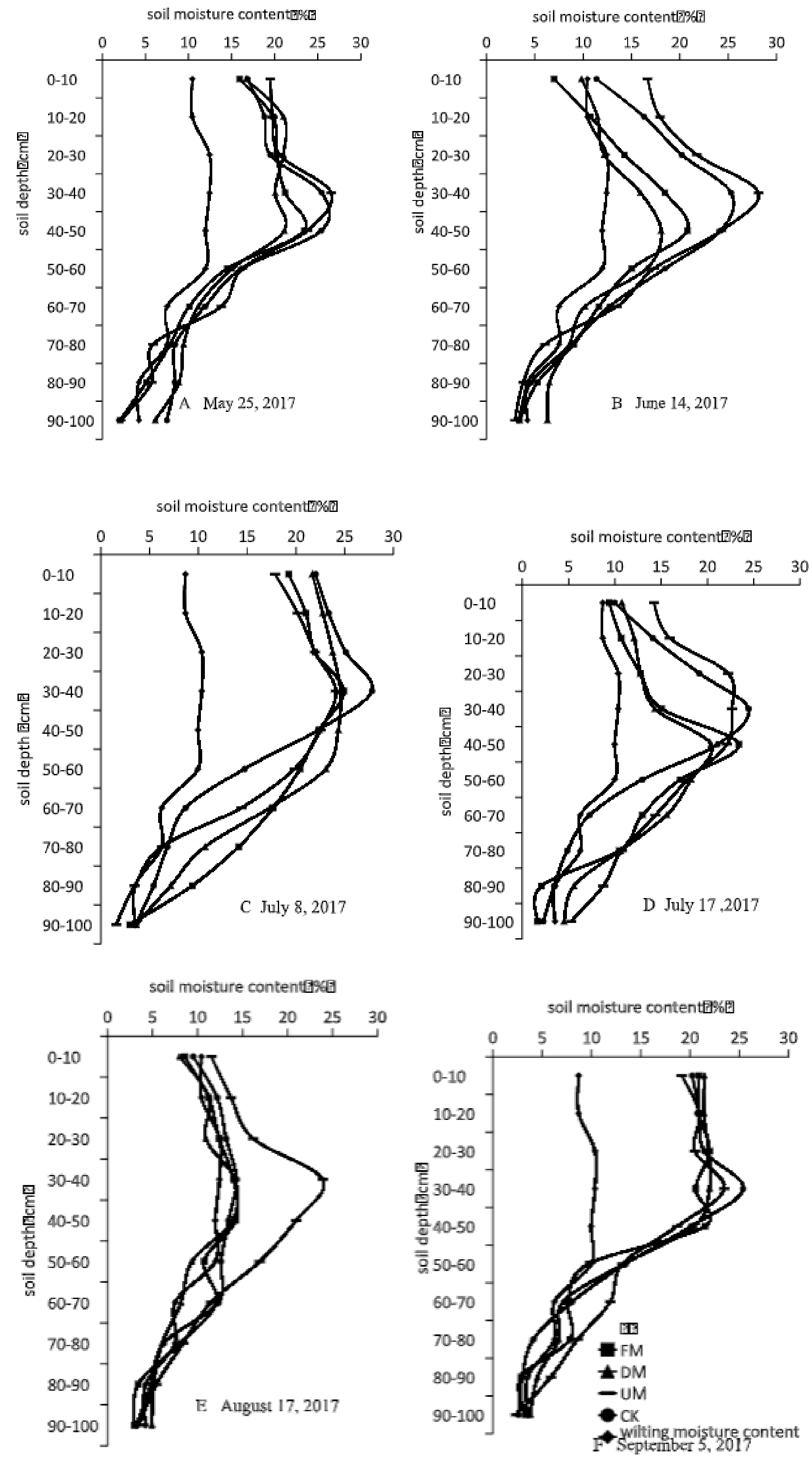

Figure 3: Dynamic changes of SMC in 0-100cm soil layers at different growth stages of maize under different plastic mulching treatments (A to F shows different measuring times).

Table 2: Yield, water consumption and WUE of maize in different treatments.

Year/period	Item	FM	DM	UM	CK
2016	Precipitation (mm)	309.8	309.8	309.8	309.8
	ET（mm）	267.0ab	265.6a	281.6b	298.0b
	Biomass (kg•ha^{-1})	12584.5a	12791.2a	8462.9b	7648.5b
	WUE (kg• ha^{-1}•mm^{-1})	47.15a	48.25a	30.15b	25.7b
	WS (mm)	223.4	232.8	48.2	-
2017	Precipitation (mm)	222.4	222.4	222.4	222.4
	ET (mm)	200.2a	201.3a	203.1a	213.1b
	Biomass (kg•ha^{-1})	9031.4ab	9734.4b	11006.2b	6424.8a
	WUE (kg•ha^{-1}•mm^{-1})	45.1ab	48.4b	54.2b	30.2a
	WS (mm)	99.3	121.5	161.8	-
5.25-7.08	Stage ET (mm)	40.9	30.8	66.6	41.6
	Biomass (kg• ha^{-1})	251.7	253.0	203.7	86.8
	WUE (kg• ha^{-1}•mm^{-1})	6.2	8.2	3.1	2.1
	WS (mm)	9.7	90.5	30.9	-
7.09-7.17	Stage ET (mm)	61.3	73.9	10.1	60.4
	Biomass (kg•ha^{-1})	403.2	941.9	486.0	141.3
	WUE (kg•ha^{-1}•mm^{-1})	6.6	12.7	48.1	2.3
	WS (mm)	111.0	328.7	197.6	-
7.18-8.17	Stage ET (mm)	88.2	100.4	100.7	82.0
	Biomass (kg•ha^{-1})	5641.2	6641.4	7977.5	3737.5
	WUE (kg•ha^{-1}•mm^{-1})	64.0	66.2	79.2	45.6
	WS (mm)	35.5	79.5	74.2	-
8.18-9.05	Stage ET (mm)	35.9	12.0	47.2	30.7
	Biomass (kg•ha^{-1})	2584.6	1460.7	1428.1	2338.4
	WUE (kg•ha^{-1}•mm^{-1})	72.1	73.1	30.3	76.1
	WS (mm)	-1.9	-0.8	-28.4	-

Note: The biomass in 2016 and 2017 was the actual yield of the plot, and the biomass accumulation at each growth stage in 2017 was calculated according to the sampling yield. Different letters in the table indicate significant differences at the 0.05 level.

that affected the spatial change of SMC were precipitation recharge, crop water consumption and soil surface evaporation. At the beginning of maize sowing (May 25), the SMC in the soil layer of 0-10 cm was lower than that of the bottom soil under the influence of the evaporation in winter and spring. It is the key for the rain-fed farming to make use of soil water at sowing and seedling emergence in time for safe production of crops.

Figure 3A shows that the SMC of 0-10 cm soil layer of UM was 16.2%, similar to that of 10-20 cm soil layer of 16.5%, which was 2 and 0.8% higher than that of CK. This is related to the film mulching under the soil surface, as it will not improve the geotemperature, but can effectively prevent soil water evaporation. The SMC of 0-10 cm soil layer decreased by 3.2, 3.6 and 1.7% as compared with 10-20 cm of FM, DM, and CK, respectively, because of the increasing temperature of FM and DM and the soil evaporation of CK.

Maize field had little rainfall during seedling stage, and the soil was in the process of water loss due to water consumption and evaporation from soil surface (Figure 3B). In June 14, the water loss of CK and UM mainly occurred in the 0-20 cm soil layer, and the water lost was 7.5% for CK; It was decreased to 1.9% due to the containment of evaporation for UM. FM and DM promoted the early growth of the seedlings (Table 3), the water loss layer was deepened to 50 cm. The water loss of FM in the 0-50 cm soil layer was 4.9%, and it was up to 5.4% for DM.

During the period from June 26 to July 8, there were 4 consecutive precipitation events and the SWS reached 52.0 mm, and each treatment increased. Figure 3C shows that the soil water storage of CK was mainly in the 0-40 cm soil layer, and the SWS increased by 8.6%. Due to the water accumulation of the film in FM and DM, the main water storage layer deepen to 60 cm, the SWS in the 0-60 cm soil layer increases by 6.3-7.2%. Also, the precipitation was absorbed into 60-90 cm, and the SWS of this layer increased by 4.9-5.2%. The SWS of UM at upper layer increment is less, and the storage layer is shallow. The water storage layer was 0-70 cm, and the SWS in each layer increased by 0.5-8.7%.

From July 8 to July 17, there was only 1 of 4.3 mm rainfall, during which the soil lost water again. Figure 3D shows that the main dehydration layers of CK, FM and DM were 0-40 cm. 0-10 cm layer of CK lost the most water with 12.1%, and decreased with soil depth. The water loss in the 30-40 cm soil layer was only 3.3%, indicating that the water loss ratio of the soil surface evaporation was larger. The water loss of the 0-40 cm layers of FM and DM was similar, and it was at the 9.8-10.7%. This means that the water absorption of root system and transpiration take the most proportion (Table 2). Figure 3D shows that only 3.9% of water loss in 0-20cm soil layer in UM is related to evaporation prevention of film.

In July 22, there was a precipitation of 32.1 mm, the water storage of each treatment increased again. From July 28 to August 17, there was only 6.4 mm precipitation (Figure 2B), each treatment showed a strong water loss process due to the rapid growth of Maize (Table 2). Figure 3E shows that the 0-60 cm layer of CK, the 0-80c m soil layer of FM and DM lost much storage water until it was close to the wilting moisture content, of which the 40-60 cm soil layer contribution ratio was the largest, while for UM the water loss in 0-80 cm soil layer was more evenly based on the higher water storage and the evaporation prevention effect of the film. The SMC of each layer of UM was the highest. In the late growth stage of maize from August 17 to September 5, the storage water of each treatment increased with the rainfall and decreased in temperature. Figure 3F shows that the transpiration water consumption and rainfall storage were parallel in the period of UM. In the harvest time, the storage water of each treatment layer was similar, and 0-60cm was the main reservoir.

The results showed that the depth of soil aquifer and water supply layer varied with rainfall and precipitation intensity in rain-fed farming area. In the semi-arid area of Northern China, the main storage layer of soil water is 0-60 cm in meadow chestnut soil. Film mulching on ridge has the effect of storing the precipitation in time and quantity, and promoting the water infiltration into soil. As compared with the traditional FM, the effect of DM is more obvious. Soil mulching has obvious effect on suppressing soil evaporation of SWS and stable water supply.

Effects of film mulching methods on water consumption and WUE of forage maize

The analysis showed (Table 2) that the amount of water consumption in maize field in two years was lower than the precipitation during the maize growth period, which was related to the late sowing and early harvest of maize in the Northern China cold region. The rainfall before the harvest supplemented the loss of soil water and the surpluses of 7.0-42.8 mm as compared with the sowing period. It is shown in Table 2 that the field water consumption of each film mulching treatment was lower than that of CK and soil water consumption of CK was 10.0-37.4 mm more than the plastic film treatment. The film mulching plays an important role in the soil water conservation.

Table 2 shows that plastic mulching significantly promoted maize growth and increased maize yield and WUE. 2016 was a rainy year; the maize yield of FM and DM increased by 64.5 and 67.2% more than those of CK, and UM increased by 10.6%. The corresponding WUE of FM, DM and UM increased by 83.3, 87.5 and 17.1%, respectively as compared with CK. The mulching treatments of FM, DM, and UM were equivalent to increase WS of 223.4, 232.8 and 48.2 mm, respectively more than CK. The effect of FM and DM was better than that of UM. 2017 was dry year, the effect of UM was better than that of FM and DM. Table 2 shows that the yield of UM was 71.3% more than that of CK, which increased by 40.6% and 51.5%, respectively than those of FM and DM, and the WUE increased by 79.5 and 49.3 and 60.3%, respectively as compared with CK. The WS of UM, FM and DM increased by 161.8, 99.3 and 121.5 mm, respectively as compared with CK.

The analysis of water consumption and biomass of different treatments at different growing stages showed (Table 2) that the warming and water retention effect of the film significantly promoted growth at early period (May 25-Jul 8) of maize. During the period, the biomass of FM and DM were 2.9 times of that of CK. This laid the material basis for the effective utilization of precipitation in the rainy season. UM could keep the water storage in soil and prevent evaporation. Under the drought environment of the middle period of maize (Jul 18-Aug 17), it could keep the stable water supply and realized the rapid accumulation of biomass of 2.1 times as high as the CK.

DISCUSSION

In SPAC, the excessive vapor pressure difference between the soil and the atmosphere accelerated the direct water dissipation through the soil surface in the semiarid area (Li et al., 2003), and the crop production was limited by the soil drought and the low temperature in the cold and dry areas. The study shows that plastic film mulching has significant effects on soil moisture conservation and temperature increase, and plays an important role in high and stable yield (Li et al., 2010).

The warming effect of plastic film promotes crop emergence, but it also causes the disorder of crop water requirement and soil water supply. The film mulching resulted in rapid growth and high spring wheat in the early stage resulting in the grain yield reduction of 40.6-49.6%

due to limited of soil water supply in the late stage (Li et al., 2001); and the film mulching of spring maize can promote the growth and development which resulted in the mismatching period of tasseling and precipitation, and the yield reduction of maize by 12.9-73.6% (Zhang et al., 2008). The present study showed that the yield of forage maize with FM and DM can increase by 40.6-67.2% than CK in the semi-arid region of Northern China. Film mulching has the effect of keeping soil moisture and increasing temperature.

According to the analysis, it is considered that the rain-fed crop production under the background of unstable precipitation in the cold arid area could choose the crop type with the longer growth period and the harvest vegetative organs, and it can give full play to the benefit of the film mulching production. The use of ridge and furrow planting and film mulching type can collect rainfall; it is more advantageous to improve the WUE. The mulching of transparent film will increase the ground temperature and promote the evaporation of soil moisture, and UM has no increasing geothermal characteristics (Tang, 2011), but there is a weakness in inhibiting the infiltration of precipitation into soil. This study showed that under the condition of soil water storage and soil water supply for crop production, the application of UM has dual advantages to effectively prevent soil evaporation and not increase soil temperature. In the saline soil with high submersible position, the water evaporation of the soil was effectively reduced by the hard shell covering of cement, and the soil water content increased significantly, and the yield of Chinese jujube increased by 31.7% (Li et al., 2000; Li et al., 2001a).

In the winter wheat field in Northern China, the yield of UM wheat with one irrigation before Jointing was equal to that of CK, it save 99.9 -118.9 mm water usage, and the WUE increased by 26.1%-34.5% (He et al., 2016). The film just under a layer of soil in UM has long life characteristics because it is free from sunlight. Therefore, it is more suitable for agricultural production in arid and semi-arid area and oasis area, especially perennial crop production. Active exploration and innovation of inter-soil irrigation and irrigation under soil (Zhang et al., 2015) have become an important aspect of the development and utilization of this film mulching method.

Conclusion

The main aquifer of the maize field in meadow chestnut soil of Northern China was 0-60 cm. The SWS during the growth period was significantly affected by precipitation and field water consumption. FM and DM had time and quantity of unstable precipitation stored in soil, promoting the effect of water infiltration, the accumulation of biomass and WUE in the early growing period of maize, increasing the yield by 40.6-67.2% in the whole growth period as compared with CK, increasing the WUE by 49.3-87.5%, and the effect was more obvious in year type with abundant water. UM had the effect of controlling the evaporation of soil surface and stable water supply, promoting the accumulation of biomass in the mid-term growth of maize, increasing the yield by 10.6-71.3% in the whole growth period, increasing the WUE by 17.1-79.5%, and the effect was obvious in the dry year.

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