EFFECT OF PLASTIC MULCHING ON WATER BALANCE AND YIELD OF DRYLAND MAIZE IN THE LOESS PLATEAU

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Keywords: plastic mulching, dryland maize, transpiration, evapotranspiration, water use efficiency

ABSTRACT

Less and varied soil-water supply is the main limiting factor for crop production in the Loess Plateau of China. A field study on dryland spring maize was conducted to investigate the effects of plastic film mulching practice on maize growth, yield, water use efficiency (WUE), soil water storages (SWS) and the ratio of transpiration to evapotranspiration (T/ET) on the Changwu Tableland of the Loess Plateau in 2013. The T characteristics of maize were measured using the sap flow method. Results showed that plastic film mulching treatment had a seedling emergence rate of 98.1%, which was significantly higher than the 80.2% of the non-mulching treatment. Maize plants reached every growth stage earlier and the whole growth period was shortened by 14 days under plastic film mulching. Soil water storage was markedly higher in plastic mulching field than in non-mulching field before July. However, at reproductive stages soil water content within the 40-150 cm profile was lower under plastic film mulching because of relatively enhancement of root water absorption. The daily mean ET under plastic mulching was lower than that under non-mulching, whereas the daily mean T was the opposite. The T/ET of maize was 68.1% under non-mulching and 85.5% under plastic mulching from July to September. Under the same LAI, the T/ET of plastic mulching was greater than that under non-mulching conditions. The plastic mulching decreased ET but increased WUE by 89.8%. It was concluded that plastic mulching is beneficial for increasing available water and improving the yield of maize on the Loess Plateau.

INTRODUCTION

The Loess Plateau is located in the upper and middle reaches of the Yellow River in China, and has an area of 640,000 km2. In this region, precipitation is the major water resources for agriculture production, and less and varied soil water supply is the main limiting factor for crop yield (Kang et al., 2002; Liu W. Z., Zhang X. C., et al., 2010). Maize (Zea mays L.) is a major crop on the Loess Plateau. However, the low temperature in spring and drought stress normally resulted in poor grain yield of this crop (Zhou et al., 2009).

Hence, management strategies to effectively use water and to sustain productivity are crucial for rainfed farming. In recent years, plastic film mulching with double ridges and furrows has been widely used in crop production in the Loess Plateau (Li et al., 2013). The ridge directs the runoff to the furrow where the water infiltrates through capillaries to inside the ridge. Planting in the furrows ensures good water moisture in the soil near the plant (Li et al., 2001). The surface film mulching favorably influences the soil moisture regime by controlling evaporation (E) from the soil surface (Raeini-Sarjaz and Barthakur, 1997). This pattern increased yield and water use efficiency (WUE) significantly in this area (Midega et al., 2013; Saindou et al., 2003; Sharma et al., 2011), due to increasing of soil temperature (Anikwe et al., 2007; Hadrian et al., 2006), augmenting of available soil water (Fisher, 1995; Wang et al., 2009), and reducing soil E from...
evapotranspiration (ET) (Li et al., 2013; Wang et al., 2011). ET, consisting of soil E and plant transpiration (T), is a major component of water balance in ecosystems (Gentine et al., 2007). However, there are very few studies to investigate plant T and soil E and T/ET on rainfed dryland maize. Therefore, our field experiments were conducted with the following objectives: (1) to measure plant T characteristics of maize under dryland farming conditions in Loess Plateau using the sap flow method and analyze the effects of plastic film mulching on the T/ET; (2) to assess the effects of plastic film mulching on soil water content at various layers and dynamics of soil water storages (SWS) during the whole maize growing period; and (3) understand the relationship between yield and soil moisture under plastic film mulching.

MATERIAL AND METHOD

Site description

The field study was conducted in 2013 at the Changwu experimental station (35.28° N, 107.88° E, approximately 1200 m above sea level) located in a typical dryland farming area on the Loess Plateau in northwestern China. The average annual precipitation in the area was 584 mm, with 466.4 mm and 307.9 mm falling between April and September (i.e., maize growth season) and between July and September (maize silking usually occurs in the middle of July), respectively. The rainfall during the spring maize growing season amounted to 520.2 mm in 2013, accounting for 90.1% of the annual precipitation (Fig. 1). The annual average temperature is 9.7°C, and the annual frost-free period is 171 d. The ground water table is at a depth of more than 50 m, making groundwater unavailable for plant growth. The soil field capacity is 20% ± 2% by weight (g/g) and wilting coefficient is 6% ± 2% (g/g). The maize variety Pioneer 335, a very popular maize hybrid in this region, was used in this study.

![Fig.1 - Precipitation distribution during 2013 compared to the long-term means (1956-2005)](image)

Experimental design and field management

In this experiment, two treatments—a control with non-mulching and treatment with plastic film mulching (Fig. 2)—were designed and applied. A planting pattern of double ridges and furrows was adopted in each treatment. The ridges were created in an alternating pattern consisting of large ridges (60 cm wide by 10 cm high) and small ridges (40 cm wide by 15 cm high). The plastic film mulching treatment involved mulching with pieces of white plastic film 120 cm wide and all ridges and furrows mulched with plastic film. In the bottom of the two ridges was the furrow where rainwater could be harvest. Each treatment was replicated three times and was applied to 40 m² (5 m × 8 m) plots arranged in randomized block design. Before ridging the treatment plots, chemical fertilizers were applied at rates of 225 kg of N ha⁻¹ in the form of urea (46% N), 60 kg of P ha⁻¹ in the form of calcium superphosphate (12% P₂O₅) and 30 kg of K ha⁻¹ in the form of potassium sulfate (45% K₂O).

In each plot, the maize was planted in the furrows with a planting spacing of 30 cm and in all treatments at a density of 65,000 plants ha⁻¹ to a depth of 5 cm using a hand-powered hole-drilling machine on April 23, 2013. During the maize growing season, the soil water supply was solely dependent on natural rainfall for all
of the treatments. The non-mulching treatment and the plastic film mulching treatment were harvested on August 25 and September 8, 2013, respectively. The sap flow was measured by the stem flow gauge on three adult plants under each treatment after the 12-leaf stage.

**Fig.2 - The Photograph and sketch of the double ridges and furrows that were mulched with plastic film**

**Measurements and data calculation**

1. **Leaf area indexes, yield and its components**

   The seedling emergence rate and growth stages of the maize were recorded. Nine plants were marked randomly in each plot for measuring leaf area indexes (LAI), located at least 1 m from plot edges and 0.5 m from previous sampling sites.

   Leaf area was calculated by multiplying their manually measured length and maximal width with a shape factor, k, empirically determined to be 0.75 for maize (McKee, 1964). The LAI value for each plot was then calculated as the product of the leaf area value and the plant density (65,000 plants ha⁻¹), i.e., LAI = leaf area (m² plant⁻¹) × 65,000(plants ha⁻¹)/10,000 (m² ha⁻¹). Shoot biomass was determined after oven drying, at 105°C for 30 min initially and then at 65-75°C for 48 h.

   At maturity, the grain yield (kg ha⁻¹) was measured for all of the plants in a 16 m² area in each plot. Weight, length and rows of the ear, ear perimeter, Kernels per row/ear and 100-kernel weight were measured. The grain yield was determined based on the average of three plot replicates, and all of the samples were dried to a constant weight by natural air drying. The mass figures are expressed in terms of air dry weight. The harvest index (%) was calculated as the air dry grain yield divided by the total above ground air dry biomass at maturity.

   A standardized maize development stage system was used to identify plant growth stages (Ritchie et al., 1992), and the date was recorded at which 50% or more of the maize plants in each plot reached the following vegetative and reproductive stages: planting time (PT), 4-leaf stage(V4), 6-leaf stage(V6), 8-leaf stage(V8), 12-leaf stage(V12), silking stage (R1), blister stage (R2), milk stage (R3), dent stage (R5) and physiological maturity stage (R6).

2. **Soil moisture content**

   The dynamic change in the gravitational soil moisture content (%) was determined using a neutron moisture meter (CNC503B). Before maize sowing, neutron probe tubes were installed in three replicated plots of each treatment, positioned in the middle of the plots. The water content in the soil profile was determined at 10 cm depth intervals down to 100 cm and at 20 cm intervals from 100 to 300 cm. The measurements were conducted approximately every five days during the maize growing season.

3. **Sap flow**

   The sap flow (g h⁻¹) was measured by the sap flow gauge. The sap flow system used in this study was a commercially available Flow32-1K (Dynamax, Houston, USA), and the gauge signals were recorded using a CR1000 Datalogger, including PC400 data logger support software that was programmed to measure at 15 sec intervals and to store the average values over 1 h periods. And the sensor type is SGB25 in this study. The sensors were mounted on different plants every seven days to prevent plant desiccation resulting from the heating of the sensor. The sap flow gauge was installed to measure the sap flow of maize plants in the same period and under the same soil moisture conditions to identify differences among sensors; these differences were not significant. Therefore, the error in this study was caused by factors other than the sensors.

   The scaling up T from single plant to whole plot requires an analysis of plant variability to correctly determine the mean plant value. This analysis was accomplished based on the variability of plant stem
diameter (Bethenod et al., 2000). The results showed a diameter classification in the range of 13 to 23 mm (Fig. 3). The crop was sufficiently homogeneous and plants with a diameter between 19 and 21 mm represented 76% of the total plants. We considered the plants belonging to this class to represent the “mean plant” in the field.

![Stem diameter distribution](image)

**Fig. 3 - Frequency distribution of the stem diameters of the maize plants that were sampled in the experimental plot (n = 100)**

(4) **Evapotranspiration**

The ET (mm) was determined by the following formula:

$$\text{ET} = \Delta W + P$$  \hspace{1cm} (1)

Where $\Delta W$ is soil water depletion (mm) between planting and harvesting in 0-300 cm soil layer, P is the precipitation (mm) during the crop growing season. ET is the sum of soil E and crop T. Because the field plots were flat and each plot was surrounded by ridges, surface runoff is near zero and precipitation infiltration below 3 m is unlikely. Therefore, the surface runoff and deep drainage are neglected.

(5) **Water use efficiency**

$WUE_T$ (kg ha$^{-1}$ mm$^{-1}$) and $WUE_{ET}$ (kg ha$^{-1}$ mm$^{-1}$) were calculated by the formulas:

$$WUE_T = \frac{Y}{T}$$ \hspace{1cm} (2)

$$WUE_{ET} = \frac{Y}{ET}$$ \hspace{1cm} (3)

Where $Y$ is grain yield (kg ha$^{-1}$), T is transpiration (mm), ET is evapotranspiration (mm).

(6) **Meteorological data**

The meteorological data during the year of experiment were measured at the Changwu automatic meteorological monitoring station situated within 50 m of the experimental field.

**Statistical analyses**

ANOVA from the SAS package was used to conduct analyses of variance.

**RESULTS**

**Seedling emergence rate and growth stage**

Seedlings (V4) emerged 6 d earlier in plastic film mulching treatment than in non-mulched plots (Fig. 4). Seedling emergence rates were 98.1% for film mulching and 80.2% for non-mulched plots, respectively. The time to the stage (V6), silking stage (R1), and maturity (R6) of maize in plastic film mulching treatment was 13 d, 9 d and 14 d shorter than in non-mulched treatment. One reason was that the plastic film mulching increased topsoil temperature during the early growth period (Liu Y., Li S.Q., et al., 2010; Zhou et al., 2009), on the other hand, soil water content was significantly increased (Zhang et al., 2014; Wang et al., 2011). Both of those reasons resulted in earlier germination and plant establishment, and enhancing the growth of maize. Similarly, each growth stage of spring maize under plastic film mulching treatment in the East of Loess Plateau emerged an average of 7 d in advance and the whole growth period shortened by 11 d as compared with non-mulching plots, the seedling emergence rates were 99.0 and 80.0%, respectively (Wang et al., 2012). The whole growth period of maize from seedling emergence to physiological maturity was 15-17 d shorter in Loess Plateau (Liu Y., Yang S. J., et al., 2010). Hence, plastic film mulching promoted maize germination and advanced growth stages.
Fig. 4 - Duration of growth stages of maize in plastic film mulching and non-mulching fields

PT, planting time; V4, 4-leaf stage; V6, 6-leaf stage; V12, 12-leaf stage; R1, the silking stage; R3, the milk stage; R5, the dent stage; R6, the physiological maturity stage. Figures with different letters are significant at the 0.05 probability level.

Soil water

SWS (0-300 cm) increased slowly at the early growth stage though precipitation was low because maize consumed only a limited amount of water at this stage (Fig. 5). However, with increasing water use of maize to maintain active growth, SWS decreased from the middle of May to early July. Because of a large amount of rainfall in July, SWS raised greatly. In the middle of July, maize reached to the silking stage and plant T was the main way of water consumption.

SWS under plastic film mulching treatment was consistently higher than under non-mulching treatment during the whole vegetative growth, with a maximum difference of 66.2 mm. That is because those large amounts of soil moisture were lost in the non-mulching treatment through soil E; most of the soil surface was exposed to direct irradiation and a dry atmosphere. Hence, the plant growth was notably restricted by the ensuing water deficit, leading to reductions in LAI and shoot biomass (Liu Y., Li S.Q., et al., 2010). However, at the reproductive stage, SWS under the non-mulching treatment was consistently higher than that in plastic film mulching plots due to that plant height and LAI under plastic film mulching reached the maximum values and significantly higher than that under non-mulching treatment, and the T of plastic film mulching was markedly higher which was the main reason of water deprivation at that stage in field (Zhang et al., 2011). Hence plastic film mulching retains soil water in the early stage to promote maize development in the later stage.

The plastic film mulching treatment significantly increased the soil water content in the upper 150 cm soil layer, compared with the non-mulching treatments, while at other depths no significant differences were observed between treatments from V4 to V8 (Fig. 6). During this period, soil water depletion was in the 0-40 cm soil profile. At V12 stage, soil water depletion was in deeper soil layer (0-150cm). As precipitation increased, the topsoil water content restored, however, the deeper layer soil water was still depleted. From V12 to R3, the plastic film mulching plots had higher water content in the upper 40 cm soil layer but lower water content at depths from 40 cm to 150 cm compared with the non-mulching plots. The cause for this was that the better water-temperature conditions in mulching treatments made individual plant taller and more vigorous, it promoted the consumption of subsoil moisture (Zhou et al., 2009). The plastic film mulching treatment used more water in the deeper soil than in the non-mulched treatment during this growth period. Soil water contents were almost similar at 150 cm for all treatments.

Fig. 5 - Dynamics of soil water storage (SWS) in 0-300 cm layer during the maize growing period. Bars show standard errors.
Transpiration and evapotranspiration

The double mass curves of cumulative T versus cumulative ET in Fig. 7 shows the changes of T/ET with time. The T was calculated by multiplying the daily accumulated sap flow per plant by a density of 65,000 plants ha\(^{-1}\). These curves showed that before August 21th T/ET was stable. And the mean T/ET was 89.1% under plastic film mulching, while it was 73.1% under non-mulching. The T/ET decreased under both treatments after August 21th. The daily mean ET under plastic film mulching was 4.9 mm and that under non-mulching treatment was 5.3 mm. Meanwhile, the daily mean T under plastic film mulching was 4.1 mm and that under non-mulching treatment was 3.6 mm.

The variation in T/ET is illustrated in Fig. 8 for the different treatments, T/ET decreased gradually from silking to maturity. From July to September the T/ET was 68.10% under non-mulching, while it was 85.50% under plastic film mulching. The values of T/ET were consistently higher in the plastic film mulching treatments than were those of the non-mulching treatment during the mid-late growth period. These results suggest that more water was used in plant T than soil surface E in the plastic film mulching treatments. Our results under non-mulching are within the range in studies in North China Plain. The T/ET of maize was 79.0% during the mid-late growth period using the sap flow gauge without mulching under dryland conditions (Zhao et al. 2009). And the T/ET of maize was 66.4% during the same period using the same method in Khorchin sandy soil (Tang et al., 2011). It was also observed that the T/ET was 61.7% to 67.7% by calculating T indirectly from measurements of micro-lysimeters (Sun et al., 2005). Plastic film mulching treatment significantly enhances the T/ET ratio compared to that of the non-mulching treatment in the mid and later stage of maize. The increased T with little soil E promoted shoot biomass accumulation and accelerate plant development in plastic film mulching plots (Liu Y., Yang S. J., et al., 2010). The T/ET of maize under both treatments decreased in the mid and later period of the growing season because of the senescence of lower leaves at late stage.
The relationship between the T/ET and LAI

From the perspective of Soil—Plant—Atmosphere Continuum (SPAC), the variations in T, ET are influenced by meteorological factors, soil (moisture) condition and vegetation factors. We compared the T/ET and LAI to analyze their relationships.

The T/ET and LAI showed a good relationship in a logarithmic function in Fig. 9. The T/ET increased logarithmically with an increasing LAI. The canopy shade conditions increased with the LAI, and the net radiation that was trapped by the canopy increased so that T and T/ET increased. When the LAI increased from 1 to 3.5, the T/ET under plastic film mulching rapidly increased from 47.9% to 84.1%, whereas that under the non-mulching treatment increased from 29.6% to 68.8%. However, with the increase in the LAI, the increasing rate of T/ET under both treatments became smaller. Under the same LAI, the T/ET of plastic film mulching was greater than that under non-mulching conditions.

Brisson proposed that The T/ET and LAI showed a relationship in a logarithmic function, the equation is: $T/ET = 1 - \exp(-\delta \text{LAI})$, where $\delta$ is coefficient (Brisson, 1992). Most studies under irrigation demonstrated that $E/ET$ and LAI was a logarithmic function. For instance, Sun et al. (2005) showed that $E/ET = 86.616e^{-0.2079\text{LAI}}$, $R^2 = 0.93$; Wang et al. (2007) showed that $E/ET = 0.9845e^{-0.345\text{LAI}}$, $R^2 = 0.93$. Our research directly studied the relationship of maize T and ET under dryland condition.
Yield, yield components and WUE

Although no significant differences between two treatments were found in kernels per row, kernels per ear and 100-kernel weight of plastic film mulching plots were significantly higher than those of non-mulching plots (Table 1). The grain yields under plastic film mulching treatment were significantly greater than those under non-mulching treatment, with concomitant increases in shoot biomass production, total T and harvest index (Table 2).

The plant T component of ET is mainly used for plant growth, whereas the soil E component of ET does not contribute to plant growth. The T under plastic film mulching treatment was significantly greater than that under non-mulching treatment. Moreover, the plastic film mulching treatment significantly increased WUE. The WUE\(\text{T}\) was 43.9 and 33.8 kg ha\(^{-1}\) mm\(^{-1}\) under plastic film mulching treatment and under non-mulching treatment, respectively. Meanwhile, the WUE\(\text{ET}\) under plastic film mulching treatment was significantly greater than that under non-mulching treatment because of the restriction of water loss from E and the increase in plant T.

Plastic film mulching plots had higher yield and WUE because plastic film mulching improved soil water storage and water use dynamics (Li et al., 2001; Zhou et al., 2009). Plastic film mulching improved soil water storage, decreased total ET but increased T/ET by reducing E and increasing T, and eventually enhanced maize development and increase grain yield and WUE (Liu Y., Li S.Q., et al., 2010, Liu Y., Yang S. J., et al., 2010; Zhang et al., 2011). However, a few studies showed that plastic film decreased gain yield. Plastic film mulching did not significantly improve the soil water storage when soil moisture was extremely low, which may intensify drought stress and increase soil temperature (Zhang et al., 2008). Therefore, plastic film mulching may be related to available soil water at planting and seasonal precipitation in different years.

Table 1

<table>
<thead>
<tr>
<th>Maize yield components for two treatments</th>
<th>Plastic film mulching</th>
<th>Non-mulching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single ear weight [g]</td>
<td>346.96a</td>
<td>251.84b</td>
</tr>
<tr>
<td>Ear length [cm]</td>
<td>18.19a</td>
<td>17.93a</td>
</tr>
<tr>
<td>Ear perimeter [cm]</td>
<td>22.19a</td>
<td>22.03b</td>
</tr>
<tr>
<td>Fruit length [cm]</td>
<td>17.79a</td>
<td>17.07b</td>
</tr>
<tr>
<td>Ear rows</td>
<td>17a</td>
<td>15b</td>
</tr>
<tr>
<td>Kernels per row</td>
<td>39a</td>
<td>39a</td>
</tr>
<tr>
<td>Kernels per ear</td>
<td>659a</td>
<td>596b</td>
</tr>
<tr>
<td>100-kernel weight [g]</td>
<td>35.65a</td>
<td>30.12b</td>
</tr>
</tbody>
</table>

Note: Figures with different letters are significant at the 0.05 probability level.

Table 2

<table>
<thead>
<tr>
<th>Grain yield and crop water-use efficiency (WUE) for the two treatments</th>
<th>Plastic film mulching</th>
<th>Non-mulching</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grain yield [kg ha(^{-1})]</td>
<td>13.144±848a</td>
<td>7591±825b</td>
</tr>
<tr>
<td>Shoot biomass production [kg ha(^{-1})]</td>
<td>22.106±1552a</td>
<td>15.780±1544b</td>
</tr>
<tr>
<td>Harvest index [%]</td>
<td>59.5±3.0a</td>
<td>48.1±2.2b</td>
</tr>
<tr>
<td>WUE(\text{T}) [kg ha(^{-1}) mm(^{-1})]</td>
<td>43.9±1.5a</td>
<td>33.8±1.2b</td>
</tr>
<tr>
<td>WUE(\text{ET}) [kg ha(^{-1}) mm(^{-1})]</td>
<td>35.5±1.8a</td>
<td>18.7±1.6b</td>
</tr>
<tr>
<td>T [mm]</td>
<td>299.1±7.2a</td>
<td>224.7±6.8b</td>
</tr>
<tr>
<td>ET [mm]</td>
<td>370.4±7.3a</td>
<td>406.5±14.6b</td>
</tr>
</tbody>
</table>

Note: Figures with different letters are significant at the 0.05 probability level.
CONCLUSIONS

To investigate the effects of plastic film mulching on maize growth, yield, WUE, SWS and T/ET, the sap flow method was used in the dryland maize fields on the Loess Plateau, China. The conclusions were obtained as follows.

2. Plastic film mulching retained soil water in the early stage to promote maize development in the later stage, and consumed more water in the deeper soil (40-150cm) during the reproductive stage.
3. Plastic film mulching decreased the daily mean ET of maize, but increased the daily mean T, and significantly enhances the T/ET ratio compared to that of the non-mulching treatment in the mid and later growth stage. The T/ET is influenced greatly by the LAI and the T/ET increases logarithmically with increasing LAI. However, under the same LAI, the T/ET of plastic film mulching was greater than that under non-mulching conditions.
4. Plastic film mulching enhanced grain yield, shoot biomass production, and harvest index. Plastic mulch also increased T, decreased ET, and with concomitant increased WUE and WUEET.

Plastic mulch is an effective way in the rainfed area of the Loess Plateau to increase water availability for higher crop yields and WUE. Whereas, it should be aware that plastic film mulching had a tendency of depleting soil water at deeper layers. Hence, further study is needed to investigate a better plastic mulch management way for maize to guarantee both high productions and system sustainability.

ACKNOWLEDGEMENT

This study was jointly supported by the National 863 Research Program of China (2013AA102904) and the National Natural Science Foundation of China (41171033).

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