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

覆膜对黄土高原旱作玉米产量与农田水量平衡的影响

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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 mulcingh 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.

摘要

基于黄土高原南部长武塬区旱作春玉米田间试验，就覆膜和露地（未覆膜）两种条件下玉米生长及蒸腾、蒸散过程进行监测与对比分析，探讨覆膜的作用与影响。蒸腾速率利用包裹式茎流计测定。结果表明：覆膜、露地处理玉米出苗率分别为98.1%和80.2%，其差异显著；覆膜提早玉米各生育阶段，缩短全生育期14 d。覆膜条件下，玉米在营养生长阶段土壤水分贮存量显著提升；然而40-150 cm土层的贮水量从7月初开始由于根系吸水相对增强而低于露地。覆膜条件下农田蒸散（ET）小于露地，而其蒸腾（T）却大于露地；7-9月露地与覆膜的T/ET分别为68.1%和85.5%；且在相同的LAI下覆膜的T/ET大于露地，土壤蒸发受到抑制。覆膜措施在降低农田耗水量的同时，随着蒸腾量的提升显著地提高了玉米产量和收获指数（P＜0.05），水分利用效率提高了89.8%。覆膜措施能增加黄土塬区旱作玉米的经济产量，并提高作物水分利用效率。

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; Saidou 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.

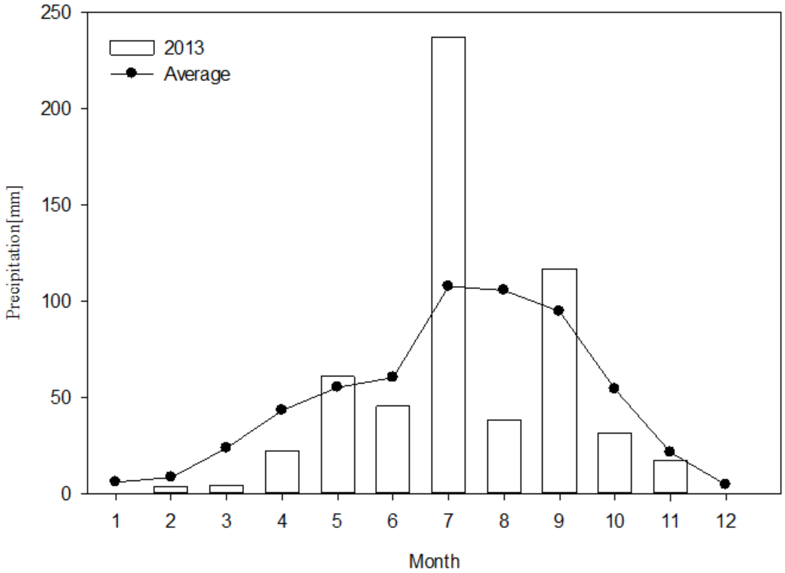

Fig.1 - Precipitation distribution during 2013 compared to the long-term means (1956-2005)

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 m^2 (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% P_2O_5) and 30 kg of K ha^{-1} in the form of potassium sulfate (45% K_2O).

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.

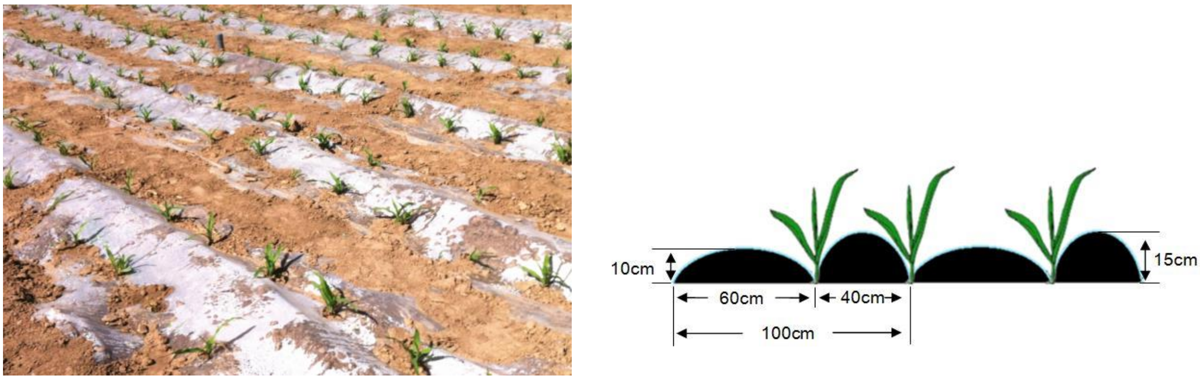

Fig.2 - The Photograph and sketch of the double ridges and furrows that were mulched with plastic film

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 (m^2 $plant^{-1}$) × 65,000(plants ha^{-1})/10,000 (m^2 ha^{-1}). Shoot biomass was determined after oven drying, at 105^{o}C for 30 min initially and then at 65-75^{o}C for 48 h.

At maturity, the grain yield (kg ha^{-1}) was measured for all of the plants in a 16 m^2 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 10cm 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.

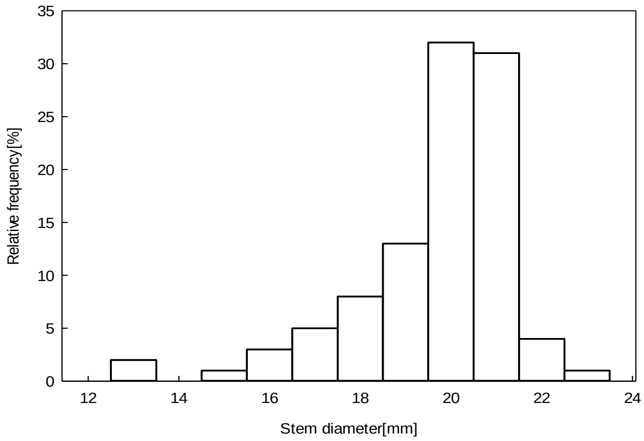

Fig.3 - Frequency distribution of the stem diameters of the maize plants that were sampled in the experimental plot (n =100)

(4) Evapotranspiration

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

$$ET = \Delta W + P \quad (1)$$

Where ΔW 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：

$$WUE_T = Y / T \quad (2)$$

$$WUE_{ET} = Y / ET \quad (3)$$

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.

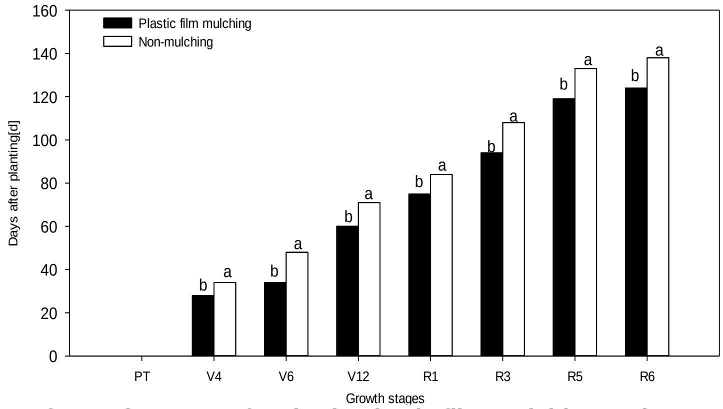

Fig.4 - Duration of growth stages of maize in plastic film mulching and non-mulching fields

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, 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.

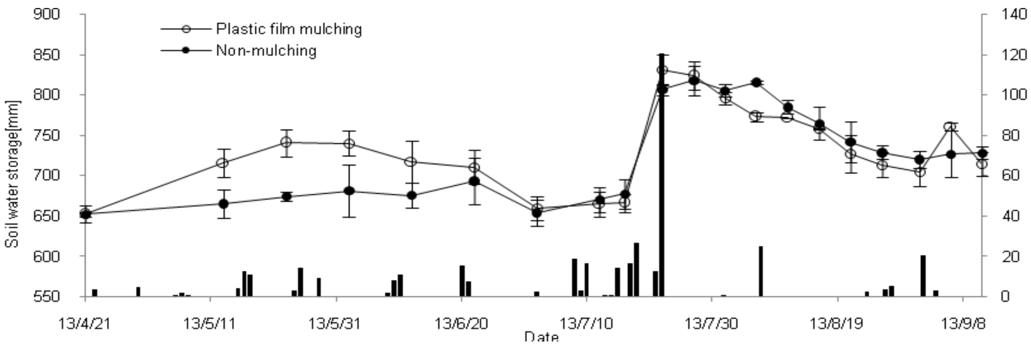

Fig.5 - Dynamics of soil water storage (SWS) in 0-300 cm layer during the maize growing period. Bars show standard errors

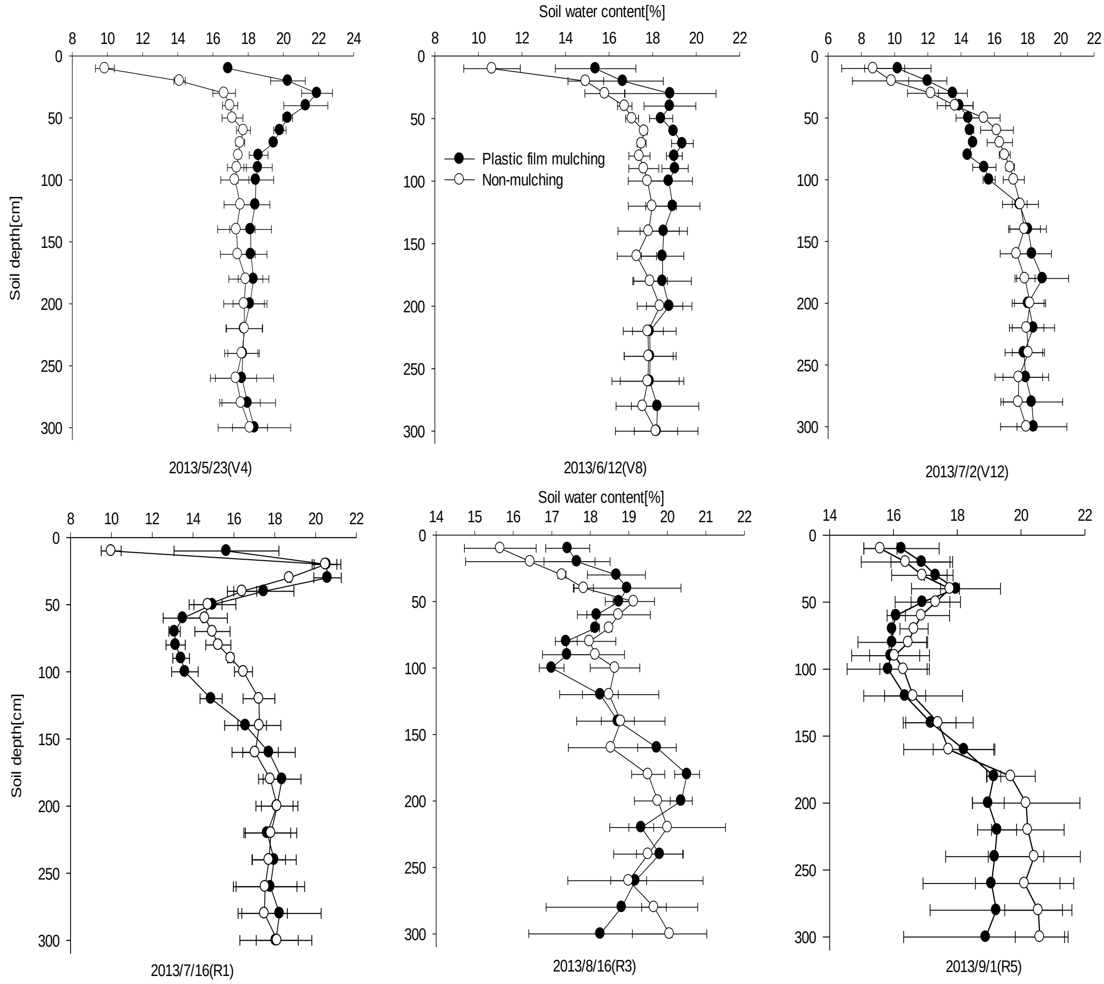

Fig.6 - soil water content in 0-300 cm layer along the soil profile in maize growing season

V4, 4-leaf stage; V8, 8-leaf stage; V12, 12-leaf stage; R1, the silking stage; R3, the milk stage; R5, the dent stage. 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 senesces of lower leaves at late stage.

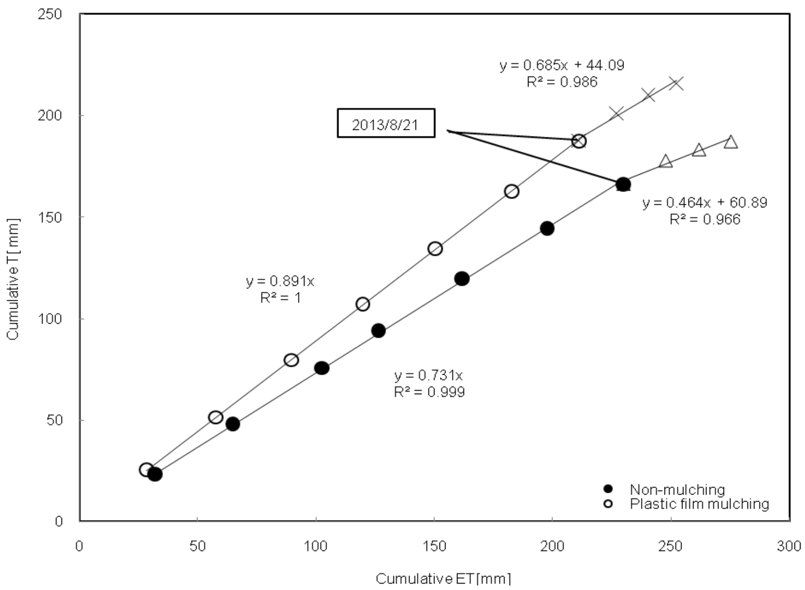

Fig.7 - Double mass curves of cumulative T versus cumulative ET of maize under two treatments during the mid-late growth period (7.16-9.8)

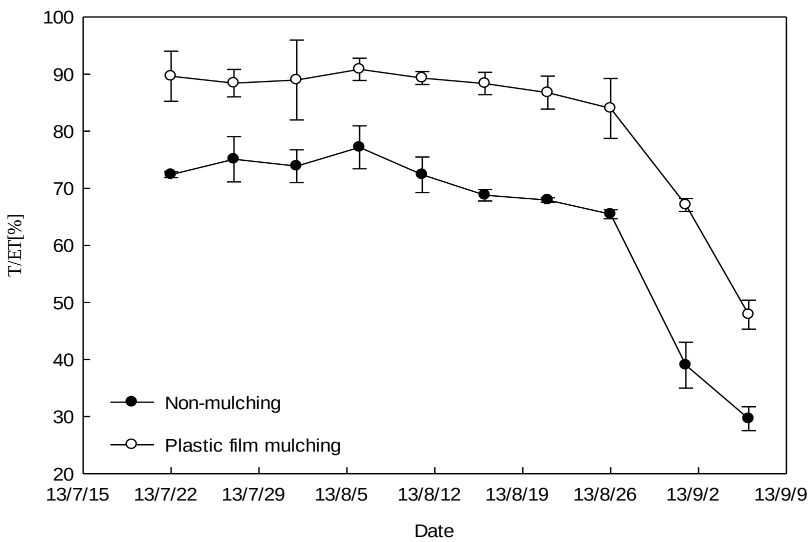

Fig.8 - Variation in the ratio of transpiration to evapotranspiration (T/ET) of maize during the mid-late growth period (7.16-9.8) for two treatments. Bars show standard errors

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.

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

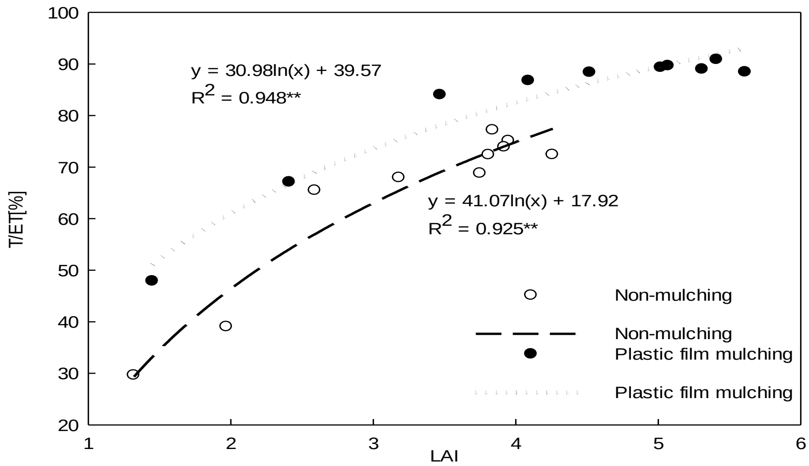

Fig.9 - Relationship between the variation in the ratio of transpiration and the evapotranspiration (T/ET) and leaf area index (LAI) during the measurement period; statistical significance level is at p< 0.01

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_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_{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

Maize yield components for two treatments

	Single ear weight [g]	Ear length [cm]	Ear perimeter [cm]	Fruit length [cm]	Ear rows	Kernels per row	Kernels per ear	100-kernel weight [g]
Plastic film mulching	346.96a	18.19a	22.19a	17.79a	17a	39a	659a	35.65a
Non-mulching	251.84b	17.93a	22.03b	17.07b	15b	39a	596b	30.12b

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

Table 2

Grain yield and crop water-use efficiency (WUE) for the two treatments

	Plastic film mulching	Non-mulching
Grain yield [kg ha^{-1}]	13,144±848a	7591±825b
Shoot biomass production [kg ha^{-1}]	22,106±1552a	15,780±1544b
Harvest index [%]	59.5±3.0a	48.1±2.2b
WUE_T [kg ha^{-1} mm^{-1}]	43.9±1.5a	33.8±1.2b
WUE_{ET}[kg ha^{-1} mm^{-1}]	35.5±1.8a	18.7±1.6b
T [mm]	299.1±7.2a	224.7±6.8b
ET [mm]	370.4±7.3a	406.5±14.6b

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.

(1) Plastic film mulching promoted maize germination and advanced growth stages.

(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_T and WUE_{ET}.

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

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