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Influence of plastic film mulch on maize water use efficiency in the Loess Plateau of China

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ABSTRACT

Water is the main limiting factor for crop growth in dryland farming areas. Plastic film mulch (PM) is widely used to improve water use efficiency (WUE) and increase crop yield over conventional methods (no mulch, NM) in China. To get a better understanding about PM influence on water use process in the field, we defined WUE_{TWI} as the ratio of yield (Y) to the total water input (TWI), and divided WUE_{TWI} into 4 steps by means of a systematic and quantitative approach. The 4 steps included ratio of available soil water (SW) to TWI ($SW_0 + P$, where SW_0 is available soil water at the sowing, P is seasonal precipitation), ratio of crop evapotranspiration (ET_C) to SW, ratio of crop transpiration (T) to ET_C and transpiration efficiency (WUE_T, Y/T). Three field experiments were conducted to analyze the influence of PM on soil moisture content, water consumption, and the grain yield of dryland spring maize (*Zea mays* L.). Results showed that, compared with NM, spring maize yield of PM was increased by 28.6%, and the WUE_{TWI} of PM was increased by 26.4% on average in the experiment 1. Since ETc with PM was slightly higher than that with NM, the ET_C/SW was increased by 3.9%. In the experiment 2, the T/ET_C with PM was 77.7% on average, 30.6% higher than that with NM; the Y/T increased by 13.6% from NM to PM. Precipitation storage efficiency increased linearly with the percentage of PM. Improved crop growth under PM led to higher crop biomass and higher leaf area index, which might result in higher transpiration rate. The T/ET_C under PM was also increased.

1. Introduction

Rainfed agricultural production systems occupy about 80% of the cultivated land in the world and produce 60% of the world's cereal grains (Rana, 2008). In China, the rainfed farming area accounts for about 25 million ha (Zhang et al., 2014).

The climate mainly belongs to semi-arid and semi-humid types in the Loess Plateau of China, with average annual precipitation between 300 and 600 mm (Kang et al., 2002). Dryland farming is the main form of agriculture in this region where the amount of rainfall is low and distributed unevenly over the year, and where available water is the primary limiting factor for crop yields. Due to the scarcity of water, mulching (e.g. plastic mulching and straw mulching) plays an important role in rainfed agriculture in these areas. From 1991 to 2011, the mass of plastic film used increased from 1.19×10^5 t to 1.25×10^6 t (National Bureau of Statistics of China, 2012). The area of agricultural land in China employing plastic film had reached about 20 million hectares by 2012. With the use of plastic film, grain crop yields in China have increased by 20%–35%. (Liu et al., 2014b).

Using 1,310 yield observations from 74 studies conducted in 19 countries, Qin et al (2015) found that plastic mulching drastically increased yields and WUE. That study proved that increased yield and WUE are widely substantiated effects of plastic film mulch use throughout the world. Theoretically, plastic film mulching can reduce soil water evaporation and thereby increase available soil water for crop growth (Li et al., 1999, 2005; Zhang et al., 2011).

Zhao et al. (2012) showed that PM increased soil water content for growth of spring maize in the Loess Plateau. Sometimes, because PM improved plant growth which consumed a greater amount of water, the soil water storage did not increase, but the crop yield and WUE increased significantly (Jiang et al., 2016; Wang et al., 2016; Zhou et al., 2009).

Generally, WUE is calculated as the ratio of the actual crop yield (Y) to the seasonal evapotranspiration (ET_C), i.e., WUE_{ET}. However, from the perspective of field water supply, ET_C is only part use from the total water input, the use efficiency of total water input (WUE_{TWI}) is also an

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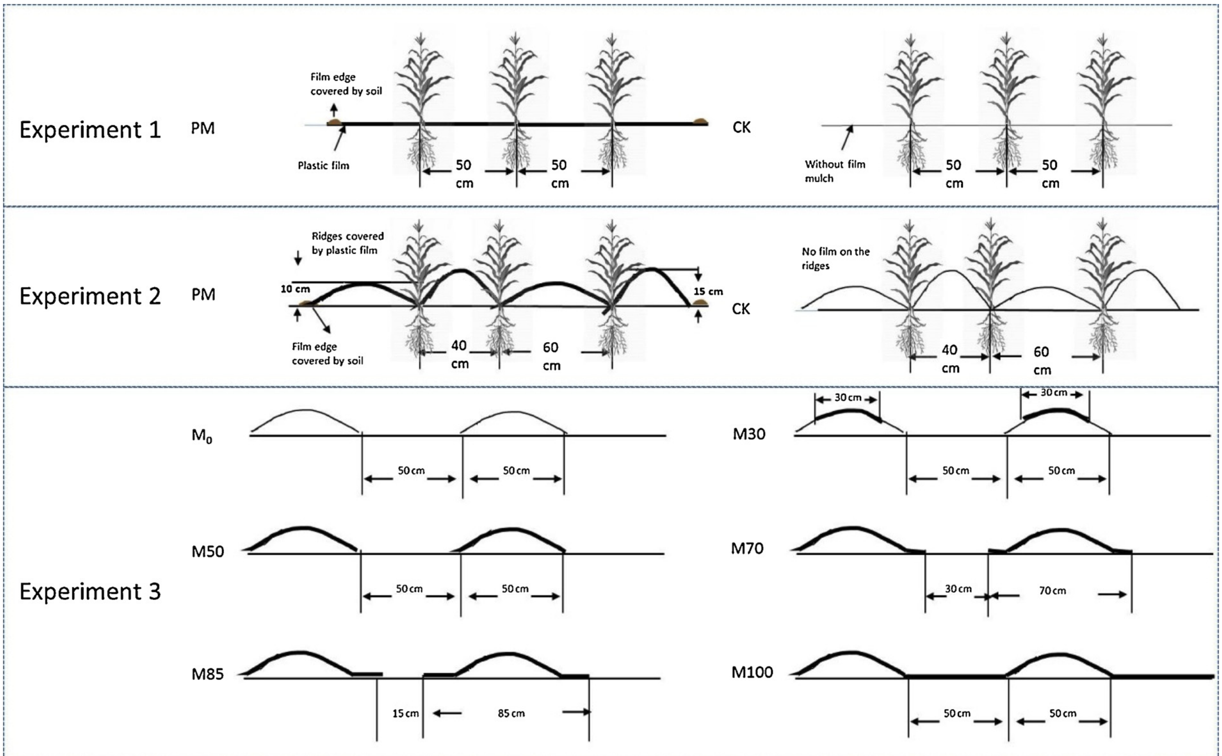

Fig. 1. Schematic diagram of the field layout. Thick lines stand for the area mulched by plastic film.

important issue. It is a systematic process from field water input to seasonal transpiration which directly relates to crop yield formation. In the literatures on agricultural water relations, both WUE and water productivity (WP) are used. According to the point of view of Pereira et al. (2012), WUE should be used to measure the water performance of plants or crops, to produce harvestable yield under the conditions of irrigation or dryland farming. In this research, we focus mainly on water performance of maize in a rainfed condition, hence WUE is used.

From a systems point of view, the agricultural production system can be considered as a simple input–output system. The inputs include nutrients, water, seed, energy etc. The outputs are crop yield and by-products such as straw. For a dryland field in the Loess Plateau, precipitation during cropping season and non-cropping season is the only source of water input. Hence water use efficiency for precipitation (WUE_P) is a reflection of WUE_{ET}. WUE_P can be defined as the ratio of output (yield) to input (precipitation), and the water use process in dryland farming can be described in several steps. Precipitation infiltrates into the soil to become stored soil water. A fraction of the soil water evaporates from the soil surface, and another fraction of the soil water is absorbed by roots and transpired to the atmosphere. Together these two processes make up ET_C. Not all soil water is used as ET_C; some soil water may be lost as deep percolation and some remains stored in the soil at harvest time.

Efficiency chain as developed by Liu (1997) and Hsiao et al. (2007) is an effective way to analyze the input/output system. The overall efficiency of any process, consisting of a chain of sequential steps, is the product of the efficiencies (output/input ratios) of each of the individual component steps (Hsiao et al., 2007). In dryland farming, where precipitation is the only source of water, WUE_p can be expressed using an efficiency chain (Liu, 1997) as:

$$WUEp = \frac{SW}{P} \times \frac{ETc}{SW} \times \frac{T}{ETc} \times \frac{Y}{T} \tag{1}$$

where SW is soil water available for evapotranspiration, which is recharged by precipitation infiltration. For a given precipitation, WUE_p reaches its greatest value when SW/P (ratio of precipitation collection and storage), ET_C/SW (ratio of water consumption on cropland during crop growth period), T/ET_C (ratio of crop transpiration to cropland evapotranspiration), and Y/T (transpiration efficiency, or WUE_T) are all maximized.

On the Loess tableland, spring maize is one of the main cereal crops. It is sown in late April and harvested in late September. Due to the limited water resources and the low accumulated temperature, only one crop per year is feasible. PM is a widely used production practice in this area (Zhang et al., 2014). Therefore, spring maize was chosen as the research crop for this study. The influence of PM on maize water use is a complex process. The objective of this research was to determine how PM influences water use process based on field experimental yield and water use data collected from three field experiments.

2. Materials and methods

We used data from three experiments to evaluate different parts of the efficiency chain. All three experiments included two treatments: no mulching (NM) and plastic film mulching (PM). Experiment 1 was carried out from 2009 to 2015. This experiment provided the results of how PM influenced maize yield and water use over seven years. Experiment 2 determined how PM influenced the distribution of T and E in ETc. Experiment 3 quantified how PM influenced soil water storage under the condition of no maize growing from April to September.

2.1. Site description

All three experiments were conducted in Changwu County, Shaanxi Province, China (35.14 N, 107.41 E and 1200–1206 m above sea level). Changwu County is located in the warm temperate zone, and has a continental monsoon climate. The average annual precipitation is 584 mm, with more than 55% falling from July to September. The average annual temperature is 9.1 °C. The soil is classified as a light silt loam (Heilutu series) with a mean soil bulk density of 1.3 g cm^{-3}. The experiments were conducted in a flat tableland area where the groundwater table is more than 80 m below the surface.

2.2. Experimental descriptions

For all the three experiments, the surface configuration is shown in Fig.1.

2.2.1. Experiment 1: Effect of PM on maize yield and water use over seven years

This experiment was conducted from 2009 to 2015, and used two management practices: (1) conventional practice (no plastic mulch was applied, NM) and (2) plastic film mulch (PM). The white transparent plastic film (0.05 mm thick, 120 cm wide) was mulched directly on the flat plot land before planting. To resist the damage of wind, the edges of the plastic films were covered with soil and the crosswise of the plastic film was covered by soil strips every two meters. The experimental design was a randomized block design with three replications; plot dimensions were 10.3 m long and 6.5 m wide. Fertilizer application amounts (135 kg N ha^{-1} and 90 kg P_2O_5 ha^{-1}) were determined by soil tests, and fertilizers were spread over the soil surface and incorporated into the 0–20 cm soil layer by a rotary cultivator before planting. Maize was planted using a handheld hole-sowing machine(drill a hole on the film to 4 cm deep, then sow the seed in the hole) in late April in rows spaced 60 cm apart at a density of 56,000 seeds ha^{-1}. The maize hybrid was 'Jinsui 9' from 2009 to 2011, and '*xianyu* 335' from 2012 to 2015.The '*xianyu* 335' is a high-yield hybrid, which was used in order to maintain similarity with local production practices.

A neutron probe access tube was installed in the center of each plot. The soil water content from 20 to 600 cm was measured using a neutron moisture meter before planting and after harvesting. Measurement depth intervals were 10 cm in the 20–100 cm layer and 20 cm from 100 to 600 cm. Soil water in 0–20 cm layer was measured gravimetrically as neutron probe measurements near the soil surface are not accurate. The neutron probe was calibrated annually to ensure measurement accuracy. The entire plot of maize was harvested manually, air dried, and weighed to determine crop yield. After harvest in late September, all aboveground plant residue was removed from plots, leaving the plastic film in the field. The plastic film was removed in the following April for the next crop planting. Weeds were controlled by hand-weeding, and no major insect problems were encountered during any growing season.

2.2.2. Experiment 2: PM influence on T/ET_C and Y/T

This experiment was conducted in 2013 and 2015. There were two management practices: NM and PM. A planting pattern of double ridges and furrows was adopted in each field. 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 PM consisted of white transparent plastic film 120 cm wide and all ridges and furrows were mulched with the plastic film. The furrow between the two ridges served to harvest rainwater. Each treatment was replicated three times in a randomized arrangement and each plot was 40 m^2 (5 m × 8 m). Before sowing, chemical fertilizers were applied at rates of 225 kg of N per ha as urea (46% N), 60 kg of P per ha as calcium superphosphate (12% P_2O_5), and 30 kg of K per ha as potassium sulfate (45% K_2O).

Sap-flow gauges (Flow32-1 K, using SGB25 sensor with CR1000 Datalogger, from Dynamax, Houston, USA) were calibrated by a weighing method of maize grown in pots and then used to determine leaf transpiration rate of maize in the field. The soil surface of pots with maize plants were completely covered by plastic film to prevent soil evaporation and hourly and daily weight losses (i.e., hourly and daily transpiration rates of leaves, respectively) of the potted maize were measured using a balance. The sap flow value was measured per hour for 3 days and the mean of the hourly values for each day was taken as the daily value to avoid the influence of plant hydraulic capacitance (Koide, 1989). There was a significant linear relationship between leaf transpiration rate measured by weight change and sap flow rate. In the field experiment, we selected 3 plants (which had the mean diameter of stems for the treatment) for each treatment to measure sap flow rate and used the sap flow value to calculate transpiration rate. The transpiration rate was then converted to the value of maize community by multiplying by the planting density.

In this experiment, leaf area was measured manually every 10 days by multiplying the length and maximal width of leaves with a shape factor, k, empirically determined to be 0.75. Leaf area index (LAI) was calculated as the product of the leaf area value per one plant and plant density (65,000 plants ha^{-1}), i.e., LAI = leaf area (m^2 $plants^{-1}$) × 65,000 (plants ha^{-1})/10,000 ($m^2\,ha^{-1}$). Soil water and yield were measured the same way as in Experiment 1.

2.2.3. Experiment 3: PM influence on soil water content with no crop present

This experiment was conducted from April 22th to September 5th in 2015. Six levels of film mulching were applied: 0% (no mulch), 30%, 50%, 70%, 85% and 100% of land covered, which were labeled as M_0, M_{30}, M_{50}, M_{70}, M_{85} and M_{100}, respectively. In each plot, ridges (50 cm width) and furrows (50 cm width) were arranged alternately.

Each test plot was 24 m^2 (4 m × 6 m), and they were arranged in a random design with 3 replications. The plastic mulch used was a white transparent polyethylene film (0.08 mm thick). The purpose of this experiment was to find out the effect of the PM on soil water conditions, so no crop was grown in this experiment. Soil water content was determined gravimetrically to a depth of 100 cm every 7–15 days and to a depth of 500 cm at the beginning and at the end of the experiment. During the experiment, herbicide was applied to the soil surface before mulching, and manual weeding was performed as necessary throughout the experimental period.

2.3. Analysis of WUE_{TWI}

From a multi-year scale, precipitation is the only water input, i.e., Eq. 1 is appropriate for a multi-year scale, or for a long-term scale. However, not only the seasonal precipitation, but also the initial soil water storage must be considered in a short-term scale. Hence, in this study we used an improved efficiency chain (Eq. 2) (Liu, 2015).

$$\mathrm{WUE_{TWI}} = \frac{\mathrm{SW}}{\mathrm{TWI}} \times \frac{\mathrm{ET}_C}{\mathrm{SW}} \times \frac{T}{\mathrm{ET}_C} \times \frac{Y}{T} \tag{2}$$

$$TWI = SW_0 + P \tag{3}$$

$$SW = SW_0 + P - R - D \tag{4}$$

Where TWI is total water input, WUE_{TWI} is water use efficiency of TWI, SW_0 is available soil water at sowing, P is precipitation, R is surface runoff from rainfall, and D is deep percolation of soil water below the measuremental depth during the period. Since the ground water is deeper than 80 m below the surface in the research area, capillary water that moves up from the deep layer to the active root zone can be neglected. The soil layer is thick and has a high holding capacity of water. In a high-yielding cropland, the amount of rainfall is not large enough to percolate into soil layer below 3 m depth in most years and only moves downward below 6 m in a few extreme wet years (Lin et al., 2016; Liu,W. et al.,2010). We measured soil water content in the 0–600 cm layer, and calculated SW to a depth of 6 m, so D can also be neglected in most years. Each experimental plot was surrounded by ridges to prevent surface runoff, so R = 0. Hence, SW = SW_0 + P and SW/TWI = 1 in this research. Note that for multi-season analysis, the ratio of SW_0 to P becomes smaller and smaller as the number of years increases, WUE_{TWI} tends to be equal to WUE_P.

2.4. Water balance and precipitation storage efficiency

ET was determined using the soil water balance equation as follows.

$$ET = P + U - R - D - \Delta W \tag{5}$$

where ΔW is soil water change in the measuremental depth, calculated as soil water storage in the 0–600 cm layer at the end of the period minus that at the beginning.

As we stated in 2.3, R = U = D = 0, hence the field water balance function was simplified to:

$$ET = P - \Delta W \tag{6}$$

In this paper, ET_C and E_C stands for evapotranspiration and evaporation during crop growth period respectively; ET_f and E_f stand for evapotranspiration and evaporation during fallow period respectively. As there was no crop during fallow period, T = 0, hence $ET_f = E_f$.

In Experiment 3, precipitation storage efficiency (PSE) (Nielsen and Vigil, 2010) during the fallow period was calculated by:

$$PSE\ (\%) = \frac{\Delta W}{P} \tag{7}$$

2.5. Statistical analysis

Mean values were calculated for each measurement and a one-way ANOVA was used to compare the effects of different practices. Least significant differences (LSD) were calculated and were deemed to be significant if $P < 0.05$. SAS 9.3 (SAS Institute, North Carolina, USA) was used for all statistical analyses.

3. Results

3.1. Yield and water use

Maize yield was significantly higher with PM than with NM throughout the seven years of the Experiment 1(Table 1). Compared with NM, yield under PM was increased by 14.0% (2009)-49.5% (2013), with an average increase over the 7 years of 28.6%. ET_C by spring maize under mulch was greater in all years except 2015, but significantly so in only four of the seven years. In 2015 ET_C was significantly greater where no mulch was present. The amount of soil evaporation during the fallow period was greater on the NM plots. Therefore, the annual water consumption was statistically the same (only 11 mm higher for NM for the 7-year mean value). During the growing season, ET_C was an average of 5.4% higher for PM. In Experiment 1, T was not measured, so $T/ET_C \times Y/T$ should be simplified as Y/ET_C, i.e, WUE_{ET}. WUE_{ET} of 7-year average was 2.61 and 2.13 kg m^{-3} for PM and NM respectively, increased by 22.5% from NM to PM.. WUE_{TWI} was 1.21 and 1.53 kg m^{-3} on average for NM and PM respectively after 7 years. Compared with NM, WUE_{TWI} was increased by 26.5% for PM. (Table 1).

Table 2
Maize grain yield (Y) and water use (T and ET_C) for two mulch management practices in Experiment 2 (2013. 2015).

Year	2013		2015	
Treatment	NM	PM	NM	PM
T (mm)	225 b	299 a	176 b	234 a
ET_C (mm)	409 a	408 a	275 a	285 a
T/ET_C	55.0% b	73.3% a	64.0%b	82.1% a
E_C (mm)	185 a	109 b	99 a	51 b
Y (kg ha^{-1})	7591b	13144a	9095 b	12424 a
Y/T (kg m^{-3})	3.38 b	4.39 a	5.18 b	5.32a

Note: NM = no mulch; PM = plastic film mulch. Means followed by the same letter in a row in the same year for each treatment are not significantly different ($p < 0.05$).

3.2. T/ET_C and WUE_T under PM

Values of T measured by sap flow gages for PM during the growing period in Exp.2 were 299 mm and 234 mm in 2013 and 2015, respectively, which were significantly higher than T for NM (Table 2). Values of ET_C estimated by water balance (Eq. 5) for PM were 408 mm in 2013 and 285 mm in 2015, compared with 409 mm and 275 mm for NM in these two years. ET_C in both years was not significantly different due to mulch treatment. The T/ET_C ratio in PM plots was 73.3% in 2013 and 82.1% in 2015 respectively, significantly higher than the 55.0% and 64.0% values measured in those two years for NM. PM significantly increased the T/ET_C ratio. WUE_T of PM was 4.39 and 5.32 kg m^{-3} respectively in 2013 and 2015, significantly higher than that of NM (3.38 and 5.18 kg m^{-3}respectively in these two years).

Transpiration rate during the season was closely related to LAI (Fig.2). T/ETc increased logarithmically with increasing LAI. Greater LAI requires more water for transpiration, and may also reduce soil evaporation due to greater ground shading by the canopy.

3.3. PM impact on soil water content

At the beginning of experiment 3, the soil water storage in the

Table 1
Precipitation, soil water balance, grain yield and water use efficiency of maize for treatments of PM and NM at Changwu County, China (2009–2015).

Treatment	Year	P_C (mm)	P_f (mm)	Y (kg ha^{-1})	W_S (mm)	W_h (mm)	ET_C (mm)	E_f (mm)	Yearly ET (mm)	SW (mm)	ET_C/SW (%)	WUE_{ET} (kg m^{-3})	WUE_{TWI} (kg m^{-3})
NM	2009	357	-	5752b	1481	1508	330 b	-	-	1234 b	26.7	1.74 b	0.47 b
PM				6556a	1541	1540	358 a	-	-	1294 a	27.7	1.83 a	0.51 a
NM	2010	543	92	8410b	1471	1615	399 a	129 a	528 a	1869 b	39.0	1.94 b	0.76 b
PM				9895a	1524	1667	401 a	108 a	508 b	1929 a	39.3	2.17 a	0.85 a
NM	2011	468	95	7616b	1546	1652	361 b	164 a	526 b	2432 b	44.8	2.00 b	0.90 b
PM				9972a	1638	1679	428 a	123 a	551 a	2492 a	47.6	2.23 a	1.06 a
NM	2012	344	245	8709b	1532	1502	375 b	365 a	740 a	3021 b	48.5	2.08 b	1.01 b
PM				11005a	1579	1519	404 a	344 b	748 a	3081 a	51.6	2.35 a	1.21 a
NM	2013	400	107	7299b	1485	1556	330 a	123 a	453 a	3528 b	50.9	2.10 b	1.07 b
PM				10914a	1516	1582	334 a	110 b	444 a	3588 a	53.6	2.51 a	1.35 a
NM	2014	268	238	8423b	1583	1496	356 b	210 a	566 a	4034 b	53.3	2.15 b	1.15 b
PM				10864a	1647	1512	403 a	173 b	576 a	4094 a	56.9	2.54 a	1.45 a
NM	2015	361	227	9513b	1537	1435	463 a	186 a	649 a	4622 b	56.6	2.13 b	1.21 b
PM				12615a	1610	1546	425 b	129 b	554 b	4682 a	58.8	2.61 a	1.53 a
NM	7-year average	392	167	7960b	1519	1538	373 a	196 a	577 a	-	-	-	-
PM				10260a	1579	1578	393 a	165 b	564 a	-	-	-	-

P_C = precipitation during growing season; P_f = precipitation during fallow period; Y = grain yield; W_s = soil water storage before sowing (0-600 cm); W_h = soil water storage at harvest (0-600 cm). SW_0 in SW was calculated as water storage above wilting point (0-600cm), 877 mm and 937 mm for NM and PM, respectively; SW = available soil water, calculated by Eq. (4); WUE_{ET} = water use efficiency of ET_C; TWI = total water input, calculated by Eq.(3); WUE_{TWI} = water use efficiency of TWI. Note that fallow period in a specific year refers to the time between harvest of the previous crop and sowing of the present crop. Yearly ET is calculated as the ET_C in growing season plus E during the fallow period. Means followed by the same letter in a column for each year are not significantly different ($p < 0.05$).

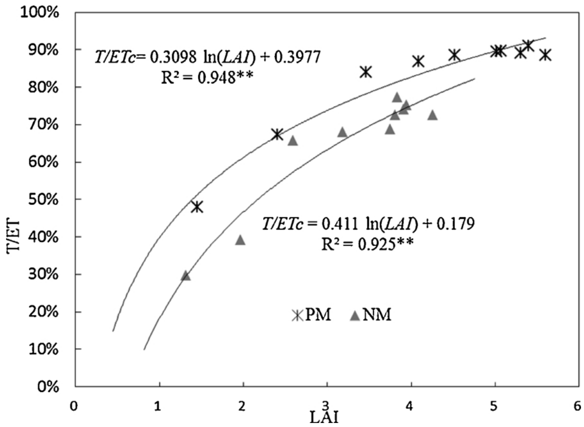

Fig. 2. The relationship between maize T/ET$_C$ and LAI at Changwu County, China. Note: T = transpiration (mm); ETc = maize evapotranspiration (mm); LAI = leaf area index. ** means that R^2 values are significant at $p < 0.01$.

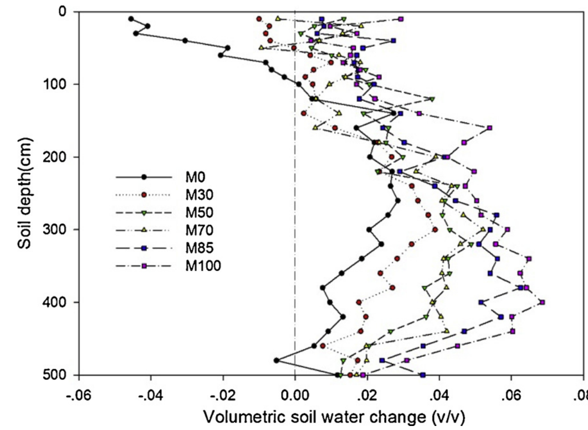

Fig. 4. Soil water change during the experiment. Values of soil water change were calculated as the difference between final soil water content (v/v) and initial soil water content (v/v).

0–100 cm soil profile was very similar in all plots, but the effect of mulch became apparent after the first month (Fig. 3). For treatment M_0, with complete exposure of the soil surface, the soil water content in the top 0–100 cm layer of both the furrow and the ridge decreased significantly and ranked as the lowest, followed by M_{30} and M_{50}, while the water content for M_{100} was the highest. The differences in soil water content among treatments in furrows were similar to that on ridges.

At the end of the experiment, the soil water content in the 0–100 cm soil layer using M_0 and M_{30} cover was less than that at the beginning (Fig. 4). The soil water content in this layer increased under all other mulch treatments. At depths below 100 cm, water content under all mulch treatments increased over the experiment period; the more the percentage of soil covered by mulch, the greater the increase in water content.

A total of 384 mm of rain fell during the experimental period and water storage increased by an amount from 44 mm to 214 mm for the 6 treatments, with the soil water increasing with the percent coverage. The sum of precipitation with < 5 mm and < 10 mm daily accounted for 13.3% and 35.5% of the total rain respectively. Such small amounts of rain can only wet the surface soil layer and likely evaporate before reaching deeper soil, and may even have evaporated directly from the upper surface of film. Soil surface mulching can reduce soil evaporation but not eliminate it. For mulch cover percentages between 0% and 85%, there was still a certain proportion of soil directly exposed to the air. Even with 100% coverage, slight soil evaporation can happen through the pores as we drilled them on the plastic film to let rainfall infiltrate into the soil. Evaporation potential was high during the experiment and soil water was prone to be lost by evaporation from the bare surface. Hence, the soil water change for all of the treatments was much below the amount of rainfall received during the measurement period.

For the M_0 treatment, only 11% of the rain received during the measurement period was retained in the soil. When 30% of the soil surface was mulched, the PSE increased to 23%. When the soil surface was fully mulched, the PSE was 56% (Table 3). We found a significant linear relationship ($p < 0.01$) between the increase in soil water storage and the percentage of mulch cover.

4. Discussion

This paper analyzed the influence of PM on maize grain yield and water use under dryland conditions in the Loess Plateau of China. A primary aim in dryland agricultural research is to provide means for the crop to use precipitation as much as possible. The partioning of WUE_{TWI} can help us understand the entire process of precipitation use by a crop, from rainfall to soil water storage, then to evaporation and transpiration. That is also why we used WUE_{TWI} rather than WUE in this study.

Generally, the maize yields harvested in these experiments were at the intermediate level for the Loess Plateau (both with NM and PM) (Lin and Liu, 2016; Zhang et al., 2014). Higher maize yields at this location have been reported, but those cases generally are the result of high resource inputs (high fertilizer applications and higher seeding rates) (Liu et al., 2014c). The use of PM increased maize yield compared with yield under the NM treatment, but the yield increase varied among years, ranging from 14.0% to 49.5% increase in yield.

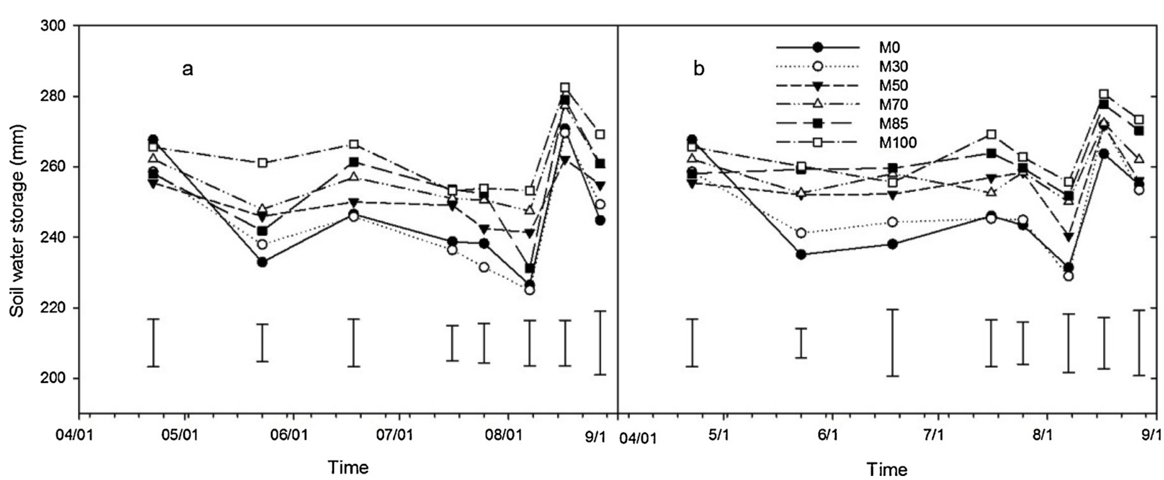

Fig. 3. Variation in soil water storage over time in the 0–100 cm soil layer. Bars show LSD 0.05 values (a: ridge; b: furrow).

Table 3
Changes in soil water storage in the 0–500 cm soil profile over the period of 22[th] April to 5[th] September as influenced by percentage of mulch. Rainfall during the experiment period was 348.2 mm.

Treatments	Water storage at beginning (mm)	Water storage in the end (mm)	ΔW (mm)	PSE (%)
M_0	1166	1210	44c	11%
M_{30}	1178	1266	88bc	23%
M_{50}	1159	1300	141abc	37%
M_{70}	1172	1311	139abc	36%
M_{85}	1158	1341	184ab	48%
M_{100}	1138	1352	214a	56%

Means of ΔW followed by the same letter are not significantly different ($p < 0.05$).

Partitioning ET_C into its component parts by using data from a field experiment is difficult. In this study, a sap flow method was used for spring maize in a field experiment to measure transpiration rate while the water balance method was used to measure ET_C. According to the sap flow data (Exp 2) the average T/ET_C ratios under NM and PM were 59.5% and 77.7%, respectively. The T/ET_C ratio under NM was higher than the result reported by Qin et al. (2013) and lower than the result from Kang et al. (2003). Irrigation may be one of the reason for higher T/ET_{ET} in Kang's research. The difference in annual P and atmospheric evaporative demand may be another reason. Reference crop evapotranspiration (ET_0) were the highest in Linyi (Qin's research), then in Changwu (this research) and Yangling (Kang's research) (Li, 2012), while P showed the opposite trend in these sites. Under dry conditions, soil water is more likely to be lost by evaporation.

T under plastic film mulch was increased (Table 2), because PM reduces soil water evaporation (Table 3) and may increase the available soil water in the root zone (Liu et al., 2009, 2014a). Higher T and lower E_C lead to a higher T/ET_C ratio. The Y/T ratio can vary for different maize varieties (French and Schultz, 1984; Liu, 1997) and field management practices. Our research showed that transpiration efficiency could be increased with PM (Table 2). Only 1%–5% of the water extracted from the soil by plants is used to produce tissue. The remaining 95%–99% of water passes into the air as transpiration (Feng et al., 2007; Yu et al., 1997). According to Liu, Y. et al. (2010), PM increased the emergence rate, promoted the growth and development of plants, and increased grain yield). In experiment 3, we measured soil temperature at 15 cm soil depth and found that soil temperature increased linearly (Supplementary Fig. 1) with increased mulch cover. Higher soil temperature is an important factor for improving maize growth in April and May.

The percentage increase in yield exceeded the percentage increase in T, so that Y/T was increased significantly. The whole growth and maturation period was shortened by 12 d, 15 d and 14 d in 2014, 2015 and 2016 respectively(Supplementary Table 1), thereby reducing the water-consuming time and the total transpiration amount for maize grown with PM Liu, Y. et al. (2010).

The ability of PM to reduce soil evaporation and hence increase water retention is widely recognized. Since stored soil water is used by crop roots in the field, it is difficult to know how well PM can increase precipitation storage when crops are present. In this study, we studied PSE when no crops were present and found the PSE could be increased from 11% under no plastic film mulch to as much as 56% with 100% soil coverage with plastic mulch (Table 3), suggesting that PM reduced E significantly and increased the water available for T, further increasing T/ET_C in the efficiency chain.

Table 4 shows how the use of PM influenced the four steps of the efficiency chain. $SW/(SW_0+P)$, ET_C/P, T/ET_C, and Y/T were increased by 0%, 3.9%, 30.6% and 13.6% respectively. The ratio of $SW/(SW_0+P)$, was assumed to reach its maximum value of 1 for both treatments so that there was no effect of PM on this ratio. This was the

Table 4
Influence of plastic film on steps of the efficiency chain.

	Step of chain	PM	NM	Increment
Experiment 1	WUE_{TWI} (kg m^{-3})	1.53	1.21	26.40%
	SW/TWI	1	1	0
	ETc/SW (%)	58.8	56.6	3.90%
	Y/ET_C(kg m^{-3})	2.61	2.13	22.50%
Experiment 2	T/ETc (%)	77.7	59.5	30.60%
	Y/T(kg m^{-3})	4.86	4.28	13.60%

result of the special conditions in this experiment, where U, R and D were equal to 0. PM increased ET_C in some of the years but reduced ET_f (Table 1). The 7-year experiment showed that annual water consumption ($ET_C + ET_f$) was the same between PM and NM (Table 1), indicating that the increase of WUE_{TWI} under PM was due to reduced Ec and increased T. ET_C/SW was also increased slightly. Over the seven years of Exp.1, PM reduced E_f, resulting in greater stored soil water at maize planting that ultimately resulted in greater ET_C and greater maize yield. Proper use of PM in this region would lead to more efficient use of the valuable limited water resource. It should be noted that in our experiments, all the plots are diked and made perfectly level to prevent runoff, so R was assumed to be 0. However, in real field situations for the tableland on the Loess Plateau, such runoff may happen sometimes since the land is not absolutely flat. Runoff amount is correlated with slope degree. When the slope was 3°and the single rain was 19.4 mm and 60.6 mm, the runoff in maize field was 0.42 and 1.02 mm respectively, accounting for 2.2% and 1.7% of the rainfall (Song et al., 2005)..

Based on the further calculation of Table 1, it was found that in the first year the WUE_{TWI} was 0.47 and 0.51 kg m^{-3} for NM and PM, respectively; WUE_P was 1.61 and 1.84 kg m^{-3}, respectively. By the seventh year, WUE_{TWI} was 1.21 and 1.53 kg m^{-3}, respectively, WUE_P was 1.49 and 1.92 kg m^{-3}, respectively. The gap between WUE_P and WUE_{TWI} decreased with the increase of years.

The efficiency chain shows that PM improved WUE_{TWI} by improving T/ET_C and WUE_T. In agricultural water management, what is required is not only a higher ET_C/SW, but also a higher T/ET_C. High values of ET_C/SW accompanied by high T/ET_C enable good crop growth and yield. The value of Y/T represents the connection between crop yield and water consumption. Many factors influence Y/T, including plant genetic properties (Feng et al., 2007; Yang et al., 2002) and soil fertility; more fertile soils generally lead to higher Y/T even with the same water consumption (Zhang et al., 1999).

5. Conclusion

The efficiency chain factored WUE_{TWI} into four steps and helped to show how to increase WUE_{TWI}. It also provides an effective way to understand and improve water management in agriculture. The experiments results show that in dryland farming areas in the Loess Plateau of China, PM increased maize yield and hence increased WUE_{TWI} significantly. By analyzing the whole water use process in the field, it was found that PM may have little impact on ET_C but it increased T and reduced E_C, resulting in spring maize T/ET_C of 73.3% and 82.1% in the two experiment years, respectively, 33.3% and 28.3% higher than that of NM. The percentage increase in maize yield exceeded the percentage increase in plant transpiration with PM, so the Y/T ratio increased.

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Declaration of Competing Interest

None.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agwat.2019.105710.

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