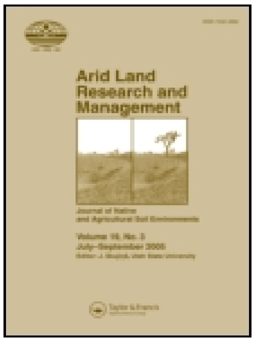

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Effects of different mulching patterns on soil moisture, temperature, and maize yield in a semi-arid region of the Loess Plateau, China

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ABSTRACT

A study was conducted in the semi-arid region of the Loess Plateau in China to identify an alternative material for use instead of plastic film under maize crops. Plastic film (PMW), straw (SMW), and biodegradable film (BMW) were used for mulching throughout the whole season (fallow and growth periods), in addition to straw for mulching (SMF) only during the fallow period. The results showed that PMW and BMW treatments retained 17 mm and 11 mm more water, respectively, than the mean value of both SMW and SMF treatments, and 53 mm and 38 mm more water than nonmulching (NM) treatment during the fallow period. PMW and BMW treatments increased the soil water and temperature during the early growth stage of maize and significantly improved the dry matter accumulation. Under PMW and BMW treatments, the yield improved by 4.6–6.4 Mg ha^{-1} and 2.3–2.8 Mg ha^{-1}, and the net income increased by 1166 USD ha^{-1} and 372 USD ha^{-1} compared with NM treatment, respectively. SMW treatment led to poor growth and yield reductions of 3.7 Mg ha^{-1} due to the lower temperature, whereas SMF treatment had no significant effects on the yield ($P > 0.05$). High water consumption with PMW treatment reduced the water supply capacity at the end of the season, and resulted in soil water deficit during 2015, indicating that high yields might not be sustained in the long-term. Therefore, BMW treatment is recommended as an effective method for increasing the maize yield and maintaining the balance of soil water in semi-arid areas.

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KEYWORDS
Mulch; semi-arid area; soil temperature; soil water; yield

Introduction

Approximately 41.3% of the earth surface's area is dryland, which supports 44% of the cultivation systems throughout the world. Agricultural productivity is low on drylands and people live in chronic poverty due to the scarcity of water resources and increasing soil degradation. Data published by United Nations Environment Program (UNEP) in 2012, gives total population of arid and semi-arid regions as two billion (30% of the world's population), and the demand for food is growing rapidly in these areas, particularly for cereal grains (UNEP 2012). Water for irrigation will be limited in the future; therefore, improving the productivity of dryland farming will become increasingly important to

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ensure food security (Stewart and Liang 2015). In China, the dryland farming area occupies one-third of the total arable area, 40% of which is located in the semi-arid northwest Loess Plateau region (Zhang et al. 2013). The problems of agricultural production in this region are complex, particularly due to variable precipitation. Maize is the most common crop cultivated in this region, where limited precipitation of 37.7 mm and an average minimum temperature of 8°C during March–May are the main restrictions on crop planting, growth and yield development (Yu, Lin, and Xu 2003).

Crop yield with dryland farming depends on the precipitation rate, which is much lower than the evaporation rate. Therefore, the key to improving the productivity of dryland farming is to increase crop water use efficiency (WUE) as well as improving soil infiltration and the retention of water. Plastic film mulching has been used widely as a management tool in arid and semi-arid areas (R. Li et al. 2012; Qin, Chi, and Oenema 2013; Feng et al. 2014). Many studies have confirmed that plastic film mulching can reduce water vapor transfer from the soil (F. M. Li, Guo, and Wei 1999; S. X. Li et al. 2013), and increase soil temperature by reducing heat exchange between the atmosphere and the ground (Acharya, Hati, and Bandyopadhyay 2005). These improved soil hydrothermal conditions can promote crop growth and increase the WUE significantly (Liu et al. 2009; F. M. Li et al. 2004). The areas where plastic film is applied have increased in recent years, but the plastic residues in farmland can be 60–90 kg ha^{-1} with a maximum of up to 165 kg ha^{-1}, which changes the soil structure, hinders the movement of moisture, gases, and fertilizer, as well as affecting the soil microbial activity, crop growth and cultivation (Yan et al. 2006). Maize yield was found to decrease by 11–23% when the amount of residues reached 58.5 kg ha^{-1} (Ma et al. 2008). Furthermore, Xue et al. (2006) found that maize biomass and yield decreased after 16 years of plastic film mulching during dryland farming. Therefore, it is important to find a replacement mulch material that facilitates sustainable agricultural production in arid and semi-arid areas.

In this study, we used plastic film, straw, and biodegradable film for mulching throughout the whole season (fallow and growth periods) from autumn (ca October 20 to November 15) in the previous year, as well as straw for mulching only during the fallow period (ca October 20 to April 15). We hypothesized that (1) mulching during the fallow period would increase the soil water content at sowing; and (2) the soil water, temperature, and maize growth would vary with different mulches. The main objective of this study was to determine whether straw or biodegradable film can replace plastic film as a mulch to improve the maize yield by relieving droughts during the early growth stage. It is hoped that the results of this study may help to reduce pollution caused by plastic film by demonstrating the suitability of an environmentally friendly mulching material for use in semi-arid areas.

Materials and methods

Site description

The experiment was conducted between November 2012 and October 2015 in Changcheng village, Pengyang County, Ningxia Province, China (35°51′N, 106°48′E; 1658 m above sea level). The annual mean air temperature was 7.4–8.5°C, the average maximum and minimum air temperature in were 19°C and −8.2°C, respectively, the annual mean sunshine duration was 2518.2 h, the annual mean pan evaporation was 1753.2 mm, the frost–free period was 140–160 days, the annual mean precipitation was 350–550 mm, and the precipitation rates during spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) accounted for 15%, 53%, 27%, and 5% of the total precipitation, respectively, during the last 40 years. The soil type was Loessal soil (sandy clay loam) with a mean bulk density of 1.40 g cm^{-3}, a field capacity of 19% (weight %), and a wilting point of 5% (weight %). The stable moisture refers to the moisture content at soil capillary rupture, which is the stable state that the soil can maintain in the long-term as well as the upper limit for dried soil layer. When the soil moisture content is between the stable moisture and the wilting point, plants can survive, but it is difficult for soil water to move or be used for crop growth. The value of stable moisture varies with precipitation among seasons and it is 50–75% of the field capacity for Loessal soil, so we considered an intermediate value (63% of the field capacity = 12%) to compare among seasons and years (Yang and Shao 2000; Jun et al. 2008). The organic matter content, and the available N, P, and K levels in the 0–60 cm soil layer were 11.63 g kg^{-1}, 50.06 mg kg^{-1}, 10.78 mg kg^{-1}, and 131.40 mg kg^{-1} respectively. The precipitation rates during the growth period in 2013, 2014, and 2015 were 590.4 mm, 317.2 mm, and 335.2 mm, respectively. The precipitation and air temperature distributions during the experimental periods are shown in Figures 1 and 2, respectively.

Experimental design and treatments

Plastic film (PMW), straw (SMW), and biodegradable film (BMW) were used for mulching throughout the whole season (fallow and growth periods), as well as straw for mulching only during the fallow period (SMF), whereas nonmulched flat planting (NM) was used as the control. The experiment employed a completely randomized design with three replicates and each plot area measured 58.8 m^2 (14 × 4.2 m). Mulching was conducted in autumn during the previous year, and the specific time is shown in Figure 3. Plastic film (clear film, 1.2 m wide × 0.008 mm thick; produced by Guyuan Yuande Plastic Products

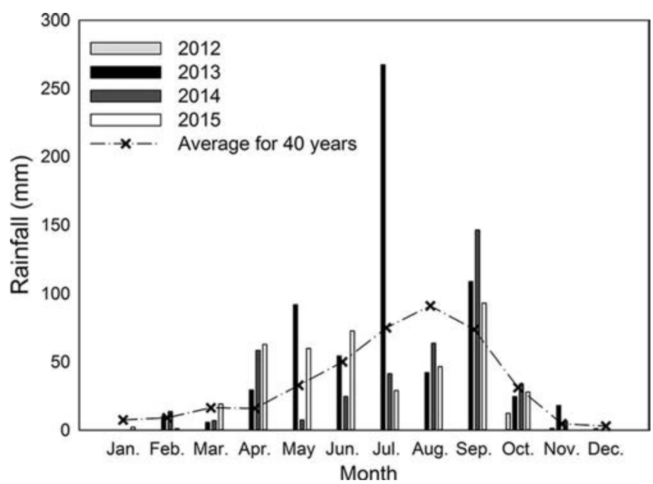

Figure 1. Precipitation distribution from October 2012 to October 2015.

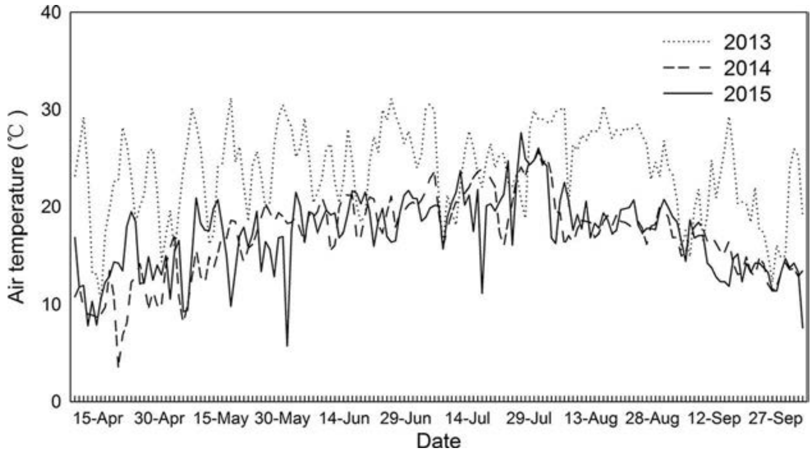

Figure 2. Air temperature during the growth period from 2013 to 2015.

Co. Ltd, Ningxia, China) and biodegradable film (1.2 m wide × 0.008 mm thick; produced by Bionolle Department, Showa Denko, Japan) were used to cover the flat surface. The white biodegradable film was an aliphatic polyester resin and it eventually degraded to yield H_2O and CO_2, where the complete degradation period of the film took about 300 days, depending on the temperature, humidity, fertility of the soil, and other factors. The edges of the film were covered carefully and compacted with soil. Every 200 cm, a soil belt was set in the vertical direction to prevent the film from being removed by strong winds. Different amounts of damage to the biodegradable film were observed in June, and the film was completely degraded after crop harvest. However, the plastic film was broken to varying degrees at harvest time, but it did not undergo complete degradation. The complete maize straw was mulched evenly at an amount of 9000 kg ha^{-1} (2–4 cm). Under SMW treatment, the straw used as mulch in the autumn was removed at sowing and then replaced after the seeds emerged to ensure seedling emergence. SMW treatment led to severe yield reductions due to the low soil temperature in 2013, so the biodegradable film which can preserve or increase soil temperature was used in 2014 and 2015, and the straw mulched in autumn was removed at the time of sowing as well as in the entire growth season (SMF). All treatments were flat planted. The maize seed cultivar "Funong 821" (dent type) was sown at a rate of 66,667 plants ha^{-1} (60 × 25 cm) using a hole-sowing/fertilization machine at a seeding depth of 4–5 cm. Fertilizer was also applied using a hole-sowing/fertilization machine, which comprised 300 kg ha^{-1} N and 150 kg ha^{-1} P_2O_5 (base, top dressing = 1:1).

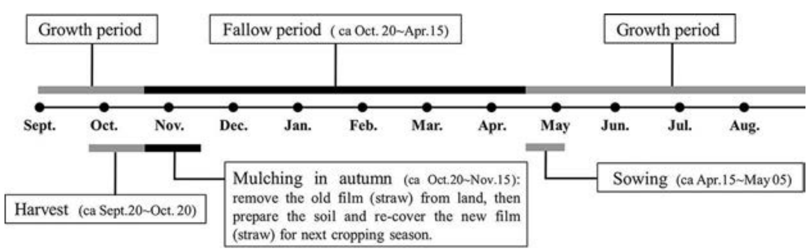

Figure 3. Timeline of the field experiment.

No irrigation was applied throughout the entire growth stage. The maize seed was sown on April 15, 29, and 17 during 2013, 2014, and 2015, respectively. The crops under plastic film or biodegradable film mulching treatments were harvested on September 28, October 23, and October 06 during 2013, 2014, and 2015, respectively. The crops under straw mulching or no mulching treatments were harvested on October 10, 23, and 16 during 2013, 2014, and 2015, respectively. Weeds were controlled manually as required during each crop growth season. No diseases were observed during the growth period with the straw mulching or other treatments.

Sample measurements and data analysis

Soil water content

The soil water content was measured gravimetrically to a depth of 200 cm in the 0–10 cm, 10–20 cm, 20–40 cm, 40–60 cm, 60–80 cm, 80–100 cm, … 180–200 cm layers. The soil samples were obtained randomly using a 54 mm-diameter steel core-sampling drill at two locations in the middle of the plant furrow for each plot. The sampling interval was 20 days from sowing, but it was delayed 3–5 days if there was rainfall on the day of sampling. The soil samples were collected in an aluminum soil box and weighed within 2 h of collection to determine the wet weight, before oven drying to constant weight at 105°C. Before sowing, the soil bulk density was determined with undisturbed soil samples using the cutting ring method (R. Li et al. 2012). The percentage of moisture in the soil by weight was calculated by dividing soil wet weight by the dried soil weight.

Soil water storage was calculated using Eq. (1):

$$SW = \sum_{i}^{n} hi \times \rho i \times bi \times 10/100, \tag{1}$$

where SW (mm) is the soil water storage, h_i (cm) is the soil layer depth, and ρ_i (g cm^{-3}) is the soil bulk density in each different soil layer, b_i is the percentage of soil moisture by weight, n is the number of soil layers, and $i = 10, 20, 40, \dots 200$.

The soil water retained during the fallow period (RSF) was calculated as the difference in soil water storage within the 200 cm layer at the time of sowing and the time of mulching (Liu et al. 2009). The water supply capacity at the end of the season (WSC) was calculated as the difference in soil water storage within the 200 cm layer under a mulching treatment and a non-mulching treatment at harvesting time.

The field evapotranspiration rate was calculated using the soil water balance Eq. (2):

$$ET = P + \Delta SW + C - D - R, \tag{2}$$

where ET (mm) is the total evapotranspiration, P (mm) is the precipitation during the growth period, ΔSW (mm) is the difference in soil water storage at sowing and harvest, C is the upward flow into the root zone, D is the downward drainage out of the root zone, and R is the surface runoff. At the experimental site, the groundwater table was located at a depth of about 80 m below the surface and, therefore, the upward flow into the root zone was negligible. Runoff was never observed because the experimental field was flat and drainage was assumed to be insignificant over a depth of 200 cm.

WUE was calculated using Eq. (3):

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

where WUE (kg ha^{-1} mm^{-1}) is the water use efficiency relative to the grain yield and Y (kg ha^{-1}) is the grain yield.

Soil temperature

A set of mercury-in-glass geothermometers was sunk into the ground between rows at depths of 5 cm, 15 cm, 20 cm, and 25 cm in every treatment plot. The soil temperatures were recorded at 08:00, 10:00, 12:00, 14:00, 16:00, 18:00, and 20:00 each day for 10 days after sowing. The daily mean soil temperature was calculated as the average of the seven intraday readings.

Plant growth index and biomass

After sowing, five representative plants from each plot were selected at intervals of 20 days throughout the growing season. The plant samples were dried in an oven at 65°C until constant weight. Four representative and undamaged rows were selected to make yield measurements in each plot, and 10 random plants in each row were harvested to measure the diameter, length, seed number per cob, and seed weight (at a standard water content of 14%).

Statistical analyses

The treatments were analyzed with SPSS 18.0 to detect significant differences by one-way ANOVA. Multiple comparisons were conducted using the least significant difference (LSD) range test, where differences were considered significant at $P < 0.05$.

Results

Soil water

Soil water at the time of sowing

Mulching inhibited soil evaporation during the fallow period and significantly improved the soil water content in the 0–200 cm layer at the time of sowing ($P < 0.05$) (Figure 4). PMW treatment increased the soil water content in the 0–60 cm layer compared with SMW (SMF) and BMW treatments at the sowing time, but with higher consumption of soil water during the previous growing season, PMW significantly decreased the soil water content in the 80–200 cm layer compared with SMF during 2014, and the soil water content in the 140–200 cm layer compared with BMW and SMF during 2015 ($P < 0.05$). PMW and BMW treatments retained more water during the fallow period, i.e., 17.13 mm and 10.86 mm more than the mean value in SMW and SMF treatments, and 53.44 mm and 38.44 mm more than that in NM treatment, respectively (Figure 5).

Soil water during the growth period

Due to the abnormally high precipitation during 2013, the soil water at harvest was higher compared with that at sowing, whereas the soil water at harvest was lower compared with that at sowing during 2014 and 2015 (Figure 6). The soil water under SMW treatment was

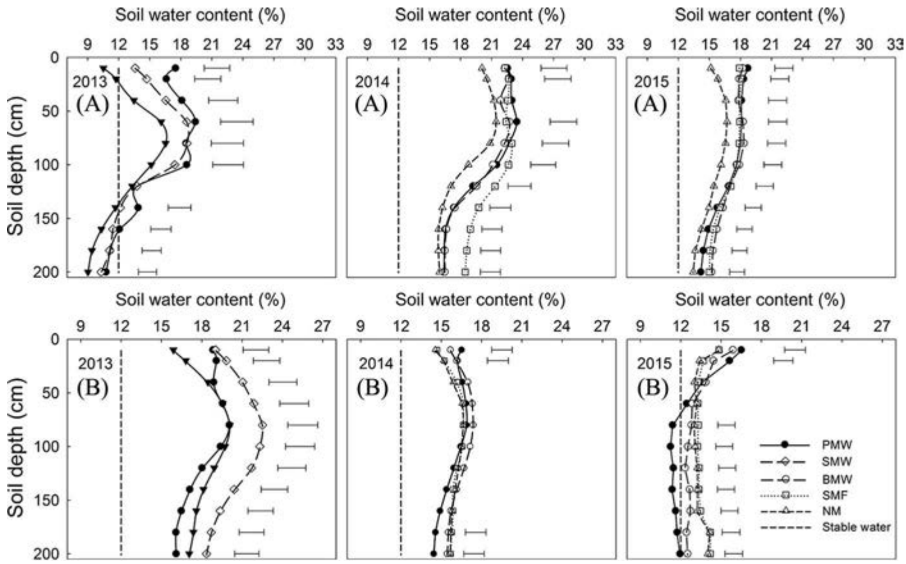

Figure 4. Soil water content in the 0–200 cm layer at the time of sowing and harvest. *Note*: (A) and (B) are the soil water content at the time of sowing and harvest, respectively; PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year. The error bars represent the least significant difference at $P < 0.05$ (LSD 0.05).

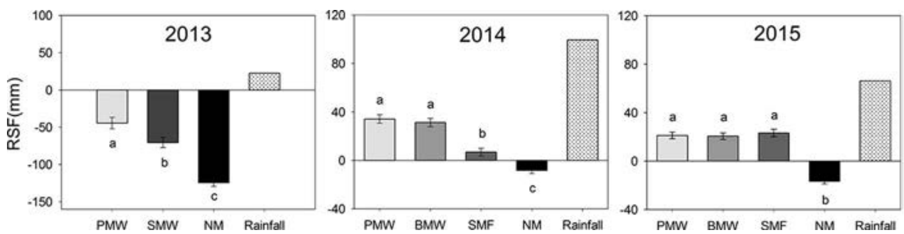

Figure 5. The soil water retained during the fallow period (RSF). *Note*: PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year. The error bars represent the standard deviations and different lowercase letters indicate significant differences at $P < 0.05$.

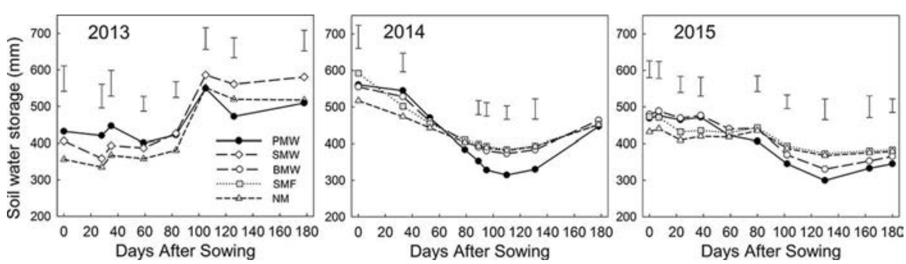

Figure 6. Soil water storage during the growth period. *Note*: PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the winter and spring fallow period; NM, no mulching throughout the year. The error bars represent the least significant difference at $P < 0.05$ (LSD 0.05).

Table 1. Yield, evapotranspiration, water use efficiency, and soil water supply capacity.

	Treatments[a]	Yield (Mg ha^{-1})	ET[b] (mm)	WUE (kg ha^{-1} mm^{-1})	SW at sowing (mm)	SW at harvest (mm)	WSC (mm)
2013	PMW	15.76 ± 1.68^{a}	512.84 ± 15.13^{a}	30.73 ± 3.27^{a}	$431.50^{c} \pm 18.81^{a}$	509.06 ± 13.47^{b}	-8.34 ± 0.22^{b}
	SMW	7.47 ± 1.35^{c}	416.16 ± 18.24^{b}	17.95 ± 3.25^{c}	406.10 ± 17.70^{a}	580.34 ± 15.35^{a}	62.94 ± 1.67^{a}
	NM	11.18 ± 1.48^{b}	428.99 ± 13.72^{b}	26.06 ± 3.45^{b}	355.98 ± 15.52^{b}	517.40 ± 13.69^{b}	—
	LSD (0.05)	1.31	31.59	2.89	34.75	28.36	2.69
2014	PMW	15.02 ± 0.91^{a}	431.46 ± 9.05^{b}	34.81 ± 2.10^{a}	560.52 ± 17.05^{ab}	446.26 ± 11.81 ns	-5.01 ± 0.13^{c}
	BMW	11.43 ± 1.47^{b}	408.53 ± 4.86^{c}	27.98 ± 3.59^{b}	554.60 ± 16.87^{b}	463.27 ± 12.26 ns	12.00 ± 0.32^{a}
	SMF	8.62 ± 1.07^{c}	456.59 ± 6.23^{a}	18.88 ± 2.34^{d}	592.03 ± 18.07^{a}	452.64 ± 11.98 ns	1.37 ± 0.04^{b}
	NM	8.60 ± 1.02^{c}	382.75 ± 6.30^{d}	22.48 ± 2.65^{c}	516.82 ± 15.72^{c}	451.27 ± 11.94 ns	—
	LSD (0.05)	0.50	12.77	1.20	31.88	22.59	0.40
2015	PMW	14.65 ± 1.55^{a}	458.71 ± 7.69^{a}	31.93 ± 3.37^{a}	468.64 ± 12.40^{a}	345.13 ± 9.13^{b}	-33.49 ± 0.89^{c}
	BMW	12.40 ± 1.07^{b}	448.47 ± 7.28^{a}	27.65 ± 2.38^{b}	478.86 ± 12.67^{a}	365.58 ± 9.67^{a}	-13.04 ± 0.35^{b}
	SMF	10.29 ± 1.10^{c}	424.99 ± 7.75^{b}	24.20 ± 2.60^{d}	472.99 ± 12.51^{a}	383.21 ± 10.14^{a}	4.58 ± 0.12^{a}
	NM	10.15 ± 1.09^{c}	388.27 ± 7.14^{c}	26.15 ± 2.80^{c}	431.69 ± 11.42^{b}	378.63 ± 10.02^{a}	—
	LSD (0.05)	0.61	13.73	1.41	23.09	18.36	1.11
Average of 2014 and 2015	PMW	14.83^{a}	445.09^{a}	33.37^{a}	514.58^{a}	395.70^{b}	-19.25 ± 0.50^{c}
	BMW	11.92^{b}	428.50^{b}	27.82^{b}	516.73^{a}	414.43^{ab}	-0.52 ± 0.11^{b}
	SMF	9.45^{c}	440.79^{ab}	21.54^{d}	532.51^{a}	417.92^{a}	2.98 ± 0.08^{a}
	NM	9.38^{c}	385.51^{c}	24.31^{c}	474.26^{b}	$414.95^{a,b}$	—
	LSD (0.05)	0.35	12.97	0.83	27.44	19.35	0.59
	Mulch	0.0000***	0.0000***	0.0000***	0.0000***[d]	0.0109*	0.0000***
	Year	0.0000***	0.0028**	0.0000***	0.0000***	0.0000***	0.0000***
Mulch × Year		0.0000***	0.0000***	0.0000***	0.1082 ns	0.0430*	0.0000***

[a]PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year.
[b]SW, soil water storage at 0–200 cm; WSC, soil water supply capacity at the end of the season; ET, evapotranspiration; WUE, water use efficiency relative to the grain yield.
[c]Values are given as the means ±standard deviations, and different lowercase letters indicate significant differences at $P < 0.05$.
[d]The probability value of an *F*-test. $^{ns}P > 0.05$; $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

significantly higher than that under NM treatment during the growth period of maize in 2013 ($P < 0.05$). The effects of SMF treatment on soil water disappeared during the growth period after the jointing stage. PMW treatment enhanced water consumption, where the WSC under PMW treatment was 71.28 mm lower than that under SMW treatment during 2013, and 18.73 mm and 22.23 mm lower than that under BMW and SMF treatments on average during 2014 and 2015, respectively (Table 1). During 2015, the soil water in the 80–120 mm layer with PMW treatment showed that there was a deficit at harvest (Figure 4) (a deficit occurred when the soil water content was lower than the stable value of 12%).

Soil temperature and developmental progress

The differences in soil temperature among treatments were obvious in the earlier stage, but they decreased with maize growth (Figure 7). PMW and BMW treatments effectively improved the temperature during the seeding stage (10 days after sowing) and the vegetative stage of maize (10–75 days after sowing) (the canopy was not closed completely). The temperature under BMW treatment was 0.9–3.7°C lower than that under PMW treatment during the growth period. During 2013, SMW treatment decreased the soil temperature by 0.5–8.4°C and 0.5–2.6°C compared with PMW and NM treatments, respectively.

Both PMW and BMW treatments improved the seedling emergence percentage, which exceeded 98%. PMW and BMW treatments clearly advanced seedling emergence and shortened the period required for growth and development. Under SMW treatment, maize growth was delayed significantly during 2013, and the maturity stage occurred 20 days and 8 days later compared with PMW and NM treatments, respectively. However, SMF treatment had no obvious effects on the soil temperature during the growth period or on the developmental progress of maize (Table 2).

Maize yield and WUE

The accumulation of biomass was increased with PMW and BMW treatments, while it decreased with SMW treatment throughout the whole growth period during 2013

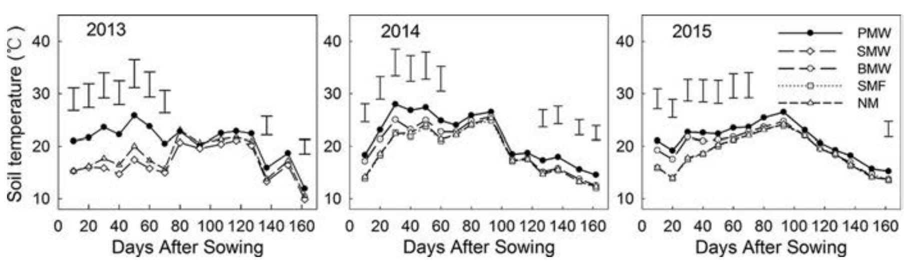

Figure 7. Average soil temperature at the depth of 5–25 cm during the growth period. *Note*: PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year. The error bars represent the least significant difference at $P < 0.05$ (LSD 0.05).

Table 2. Growth and developmental progress (days after sowing) and emergence rate (%).

	Treatments[a] a	Emergence rate (%)	Emergence (d)	Jointing (d)	Flowering (d)	Filling (d)	Maturity (d)
2013	PMW	99.0	12	38	90	101	158
	SMW	87.2	18	55	113	123	178
	NM	85.4	18	52	103	116	170
2014	PMW	99.8	6	35	76	88	152
	BMW	98.6	8	42	87	98	163
	SMF	95.3	17	50	95	104	169
	NM	94.0	17	50	95	104	169
2015	PMW	99.4	9	39	86	100	157
	BMW	97.9	12	46	98	113	171
	SMF	93.6	19	53	104	120	178
	NM	92.5	19	54	104	120	178

[a]PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year.

($P < 0.05$) (Figure 8). Under PMW and BMW treatments, the yield improved by 4.58–6.42 Mg ha^{-1} and 2.25–2.83 Mg ha^{-1} compared with NM treatment, respectively, which significantly improved the WUE ($P < 0.05$). SMW treatment led to a yield reduction of 3.71 Mg ha^{-1} and decreased the WUE by 8.11 kg mm^{-1} ha^{-1} compared with NM treatment during 2013. The water stored in the autumn under SMF treatment was not utilized effectively by the crop as grain yield, where the field ET increased and the WUE decreased by 2.77 kg mm^{-1} ha^{-1} compared with that under NM treatment (Table 1).

Economic benefit

BMW treatment increased the cost of materials compared with PMW treatment, but reduced the labor costs incurred by removing the film from the field after crop harvesting. PMW and BMW treatments increased the average net income by 1166.3 USD ha^{-1} and 371.9 USD ha^{-1}compared with NM treatment, respectively. In contrast, the net income under SMW and SMF treatment were 1624.3 USD ha^{-1} and 359.2 USD ha^{-1} lower compared with NM treatment, respectively, due to the decreased output/input ratio (Table 3).

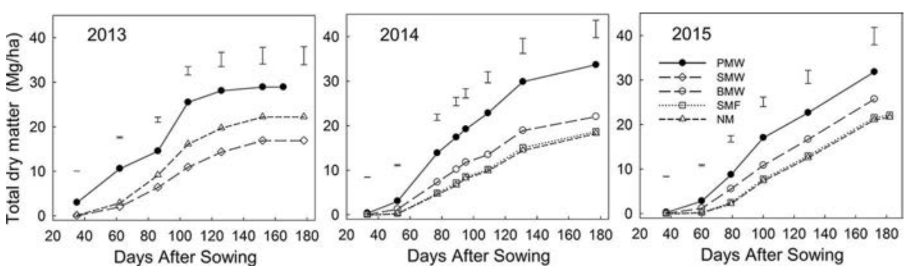

Figure 8. Biomass accumulation of maize. *Note*: PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year. The error bars represent the least significant difference at $P < 0.05$ (LSD 0.05).

Table 3. Economic output and input ($/ha).

	Treatments[a]	MMI[b]	SFI	LI	TI	TO	NI	Benefit over NM	O/I
2013	PMW	202.5	429.7	531.0	1163.2	5295.0	4131.8	1075.7	4.6
	SMW	135.0	429.7	513.0	1077.7	2509.5	1431.8	−1624.3	2.3
	NM	0.0	429.7	270.0	669.7	3755.9	3056.2	—	5.4
2014	PMW	202.5	429.7	531.0	1163.2	5317.2	4154.1	1808.3	4.6
	BMW	236.3	429.7	432.0	1097.9	4047.0	2949.0	603.3	3.7
	SMF	135.0	429.7	513.0	1077.7	3051.7	1974.0	−371.8	2.8
	NM	0.0	429.7	270.0	669.7	3045.4	2345.8	—	4.4
2015	PMW	202.5	429.7	531.0	1163.2	3515.5	2352.3	615.1	3.0
	BMW	236.3	429.7	432.0	1097.9	2975.8	1877.8	140.6	2.7
	SMF	135.0	429.7	513.0	1077.7	2468.4	1390.7	−346.5	2.3
	NM	0.0	429.7	270.0	669.7	2436.9	1737.3	—	3.5

[a]PMW, BMW, and SMW represent mulching with plastic film, biodegradable film, and straw, respectively, throughout the whole season (fallow and growth periods); SMF, straw mulched only during the fallow period; NM, no mulching throughout the year.

[b]MMI, mulching material input; SFI, seed and fertilizer input; LI, labor input; TI, total input = MMI + SFI + LI; TO, total output; NI, net income; O/I, output: input ratio = TO/TI.

[c]Plastic film cost 1.93$/ kg, maize straw cost 0.015$/ kg, biodegradable film cost 2.25$/ kg; maize seed cost 0.34, 0.35, and 0.24$/ kg in 2013, 2014, and 2015, respectively. The exchange rate for US dollar to Chinese RMB was 0.15:1.

Discussion

Soil water

In the semi-arid areas of northwest China, frequent spring droughts lead to low seedling emergence and poor plant growth, resulting in variable and low yields (Zhang et al. 2014). The results of our study demonstrated that mulching during the fallow period effectively increased the soil water content at the time of sowing. Plastic film allowed the movement of water from the deep layer to the surface layer (F. M. Li, Guo, and Wei 1999), and thus PMW treatment was more effective in improving the soil moisture in the 0–60 cm layer at sowing. Qin, Chi, and Oenema (2013) stated that plastic film was less suitable for use during fallow periods compared with straw because film mulching could reduce rainwater infiltration and increase the runoff rate. However, in the present study, rainfall was much lower than evaporation during the winter and spring fallow period, and we found that the effects of plastic film and biodegradable film mulching on suppressing evaporation were superior to that of straw, thereby retaining more water in soil during the fallow period, which agreed with the results of Zhang et al. (2013).

Mulching with plastic film can enhance the consumption of soil water, but its effects on soil water balance were inconsistent with studies under the semi-arid areas, mainly due to the varied distributions of rainfall. With less than 250 mm rainfall during the crop growth period, F. M. Li et al. (2004) and H. Zhao et al. (2012) reported that the soil water was consumed too rapidly under plastic film mulching, and a critical water deficit occurred during the late growth stage. However, Liu et al. (2014) suggested that plastic film mulching can maintain the soil water balance under >273 mm annual rainfall because the soil water consumption could be compensated for during the late period of maize growth when the crop water demand decreased and the rainfall increased. We found that the soil water recovery under PMW treatment was influenced by the amount of rainfall from July to September. The amounts of rainfall from July to September during 2013 and 2014 were 178 mm and 11 mm higher than the annual average, respectively, and the soil water content was almost restored at harvest under PMW treatment. But the amount of rainfall from July to

September in 2015 was 71 mm lower than the annual average, and the soil water in the 80–200 cm layer under PMW treatment had a deficit at harvest (0.43–6.33% lower than the stable soil water content) (Figure 4). It is difficult to replenish soil water deficit in deep layers due to plastic film mulching and further increases in this deficit will probably lead to yield reductions, thereby preventing sustainable production due to low water availability. However, BMW treatment decreased the water use compared with PMW treatment, thereby supporting recovery of the soil water content, which avoided the yield failure caused by droughts during the middle and late growing seasons; thus, using biodegradable film mulching can facilitate more sustainable maize production with uncertain of rainfall distributions in semi-arid areas.

Soil temperature and maize yield

Maize is highly sensitive to temperature and low temperature during spring in the semi-arid areas of northwest China often slows down germination and delays crop growth (Liu et al. 2009; L. D. Bu et al. 2013). Our results showed that both PMW and BMW treatments increased the soil temperature during the germination and vegetative stages in maize, thereby improving the rate of emergence and accelerating the growth progress (biodegradable film with a long degradation period and stable performance was selected after considering that the long covered stage might affect heat retention). The low rate of light transmittance under the biodegradable film did not increase the temperature as greatly compared with the plastic film, which was a similar observation to that of R. Li et al., (2012) and Subrahmaniyan and Zhou et al. (2008). In addition, with the growth of maize, the degradation of the biodegradable film could have been aggravated by the increasing air temperature and rainfall. Thus, the soil temperature under BMW treatment was lower than that under PMW treatment throughout the growth period, which impaired maize growth and development to reduce the yield by 2.9 Mg ha^{-1} compared with PMW treatment.

Many studies have demonstrated that straw mulching can increase the crop productivity by conserving soil water in drought areas where soil water was the first limiting factor for crop growth (Amir and Sinclair 1996; Huang et al. 2005; Y. G. Zhao et al. 2014). In present study, SMW significantly decreased the soil temperature because the mulched straw hindered the access of solar radiation and reduced the thermal conductivity (Fernandez et al. 2008; R. Li et al. 2012). The mean annual air temperature in the study region was 7.4–8.5°C, indicating that heat is also the primary factor limiting production, thus the decrease in soil temperature under SMW treatment led to growth retardation and yield reductions of 3.71 Mg ha^{-1} (33.18%), even though the soil water storage was improved during the growth period, and these results agree with those obtained by Fernandez et al. (2008) and Subrahmaniyan and Zhou (2008). After considering the yield failure with SMW during 2013, the straw was removed at the time of sowing during 2014 and 2015. However, the stored water under SMF treatment was lost rapidly due to the low precipitation and intense evaporation in the early stage of maize growth. Thus, the soil water stored during the autumn was not utilized effectively by the crop, which increased the field evapotranspiration and decreased the WUE by 2.77 kg mm^{-1} ha^{-1} compared with that under NM treatment, which explained the importance of soil water conservation in dryland farming of semi-arid areas.

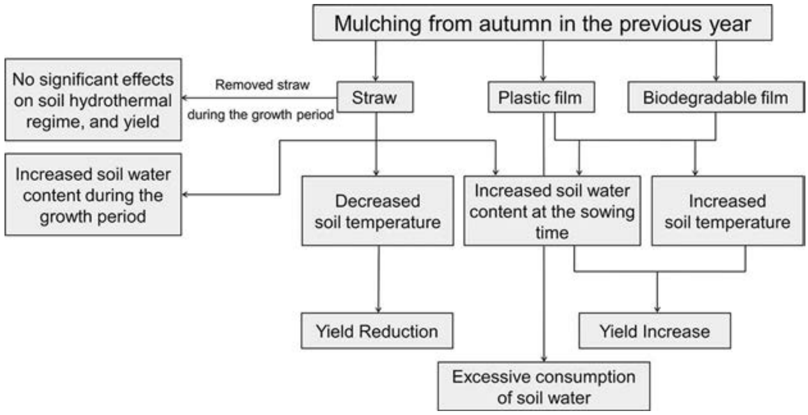

Figure 9. Processes employed by the different mulching treatments.

Y. S. Bu et al. (2006) suggested that plastic film should be selected if the main aim is to increase soil temperature, whereas straw should be selected if the goal is to increase soil moisture. Our results also indicate that the soil temperature and soil moisture are equally important for crop productivity in semi-arid areas of the Loess Plateau, China, where PMW and BMW treatments obtained the required hydrothermal conditions during the earlier stage of maize growth, which was more effective at increasing the biomass accumulation and maize yield compared with straw mulching. And the processes of different mulching treatments with respect to soil hydrothermal regime and yield are summarized in Figure 9.

The greater yields with PMW treatment resulted in higher economic benefits compared with BMW treatment, but PMW treatment also causes environmental problems in the long term. According to previous research, the total amounts of plastic film residues in the soil were $3.2–6.4 \times 10^4$ t in 1991 and $9.3–18.6 \times 10^4$ t in 2004, i.e., an increase of almost three times during 13 years in China (Yan et al. 2006). Dong et al. (2013) also showed that the number and weight of plastic residues increased by 4.0×10^5 pieces ha^{-1} and 13.7 kg ha^{-1} per year, respectively, due to annual increases in mulching. Hence, it is essential to select environmentally friendly mulching materials to facilitate sustainable agricultural production in the future. In addition to reducing the yield, straw mulching may influence farm operations because the crop straw only decomposes slowly in cold semi-arid areas (Feng et al. 2014). By contrast, biodegradable film eventually degrades to water and carbon dioxide around the harvest time, and it only has minimum impact on the soil environment, as well as reducing the requirements in terms of labor and material resources for ground cleaning and mulch recycling.

Conclusion

In dryland farming, drought is the primary factor that limits crop production due to the uneven distribution of precipitation. In this study, we showed that the effects of mulching on the soil moisture and temperature are equally important for crop productivity in semi-arid areas of the Loess Plateau, China. Mulching with plastic film and biodegradable film throughout the whole season obtained the required hydrothermal conditions during the earlier stage of maize growth, thereby improving the yield by 4.6–6.4 Mg ha^{-1} and 2.3–2.8 Mg ha^{-1}, respectively. The decreased soil temperature under straw mulching led to yield losses, thereby making it unsuitable for use in cold semi-arid areas. Plastic film mulching resulted in soil water deficiency, and it causes soil pollution problems, thereby hindering sustainable crop production compared with biodegradable film mulching. However, encouraging farmers to accept a trade-off between promoting environmental benefits and income losses may be the greatest challenge that hinders the uptake of biodegradable film, which will need the support of the government.

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