Soil mulching can mitigate soil water deficiency impacts on rainfed maize production in semiarid environments

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Abstract
Temporally irregular rainfall distribution and inefficient rainwater management create severe constraints on crop production in rainfed semiarid areas. Gravel and plastic film mulching are effective methods for improving agricultural productivity and water utilization. However, the effects of these mulching practices on soil water supply and plant water use associated with crop yield are not well understood. A 3-yr study was conducted to analyze the occurrence and distribution of dry spells in a semiarid region of Northwest China and to evaluate the effects of non-mulching (CK), gravel mulching (GM) and plastic film mulching (FM) on the soil water supply, plant water use and maize (Zea mays L.) grain yield. Rainfall analysis showed that dry spells of ≥5 days occurred frequently in each of 3 yr, accounting for 59.9–69.2% of the maize growing periods. The >15-d dry spells during the jointing stage would expose maize plants to particularly severe water stress. Compared with the CK treatment, both the GM and FM treatments markedly increased soil water storage during the early growing season. In general, the total evapotranspiration (ET) was not significantly different among the three treatments, but the mulched treatments significantly increased the ratio of pre- to post-silking ET, which was closely associated with yield improvement. As a result, the grain yield significantly increased by 17.1, 70.3 and 16.7% for the GM treatment and by 28.3, 87.6 and 38.2% for the FM treatment in 2010, 2011 and 2012, respectively, compared with the CK treatment. It’s concluded that both GM and FM are effective strategies for mitigating the impacts of water deficit and improving maize production in semiarid areas. However, FM is more effective than GM.

Keywords: semiarid areas, plastic film mulching, gravel mulching, dry spell, evapotranspiration, maize yield

1. Introduction

Water and its efficient use are a growing major concern for agricultural production worldwide, particularly in dryland regions (Rockström et al. 2007; Vörösmarty et al. 2010). Approximately 18% of the Earth’s land surface is semiarid land that is indispensable for global food production (UNEP 2007). Limited groundwater, low precipitation and high water losses combine to make water scarcity the main
limiting factor for primary production in rainfed semi-arid areas (Deng et al. 2006; Hatibu et al. 2006). However, some studies have indicated that an irregular temporal distribution and inefficient management of rainwater, rather than total rainfall, are the primary constraints on crop production (Barron et al. 2003; Rockström et al. 2010). Studies have reported that adopting optimized water and soil management strategies to bridge water limitations during dry spells can markedly promote crop growth and increase yields (Barron et al. 2003; Liu et al. 2010; Rockström et al. 2010; Nyakudya and Stroosnijder 2011; Li et al. 2013). With the population continuously growing, improving rainwater management to mitigate the negative impacts of water deficiency and increase water productivity in semi-arid areas is crucial to ensuring future food security.

Soil surface mulching is a common and effective practice for offsetting water limitations in agricultural production. Gravel mulching (GM), an important traditional technique, has been used for many years worldwide (Lemon 1956; Modaihsh et al. 1985; Nachtergaele et al. 1998; Li 2003; Yamanaka et al. 2004; Li et al. 2005; Wang et al. 2011). In addition, plastic film, an artificial material, has also long been used (Clarkson 1960; Andrew et al. 1976). With the rapid development of modern industry, the use of plastic film mulching (FM) has greatly increased in recent years (Li et al. 2001, 2013; Anikwe et al. 2007; Liu et al. 2009; Zhou et al. 2009, 2012; Sharma et al. 2011). Numerous studies, such as those mentioned above, have reported that both the gravel and plastic film mulching techniques can effectively alleviate a water deficit by capturing rainfall and reducing soil evaporation. This increases soil water availability and dramatically improves crop yields, particularly in dryland farming systems. However, crop response to water stress or water supply varies during different growth stages. Moser et al. (2006) reported that pre-anthesis drought delayed the maize silking stage and shortened the grain filling duration, leading to 13–32% lower grain yield compared with well-watered maize. On the mostly semiarid Loess Plateau of China (Li 2004), maize was found to be sensitive to water deficit during the stem-elongation stage, and limited irrigation at this stage could increase the grain yield and water use efficiency (WUE) (Kang et al. 2000). Zhang et al. (2014) reviewed research on management strategies and found that maize grain yield linearly increased with increases in pre-silking water use, whereas no relationship was found between yield and post-silking water use. These differences were primarily attributed to the uneven distribution of rainfall and changing plant water requirements during different growth stages. Few studies have focused on yield formation associated with soil water supply and crop water use during different growth stages of mulched crops (Liu et al. 2010). Progress in addressing this issue will be extremely beneficial for informing rainwater management strategies to improve crop production in rainfed semi-arid areas.

We conducted a 3-yr field study on the Loess Plateau to explore the effects of gravel and plastic film mulch on rainfed maize systems; maize is one of the dominant crops in the region (Zhang et al. 2011). Our objectives were to (i) evaluate limitations on maize production due to the total rainfall and timing of dry spells and (ii) determine the effects of two mulching techniques on the soil water supply, plant water use and maize yield.

2. Results

2.1. Precipitation, reference evapotranspiration and dry spell

The precipitation during the maize growing season was 496 mm in 2010, 487 mm in 2011 and 363 mm in 2012, accounting for 84, 76 and 76% of the annual precipitation, respectively (Fig. 1). Compared with the long-term average (1957–2009), precipitation during the maize growing season was 70 mm higher in 2010, 61 mm higher in 2011 and 63 mm lower in 2012. However, the intra-annual distribution of precipitation in the 3 yr was as same as over the longer term, i.e., much more rain fell late in the growing season. From the sowing to the silking stage (middle of July), the precipitation was 96 mm in 2010, 150 mm in 2011 and 165 mm in 2012. In contrast, 399, 337 and 198 mm fell from the silking to the maturity stage. This pattern most likely caused severe water stress before the silking stage.

The diurnal reference evapotranspiration (ET₀) displayed large fluctuations during the maize growth season, ranging from 0.5 to 10.7 mm d⁻¹ in 2010, from 0.5 to 8.6 mm d⁻¹ in 2011 and from 0.9 to 8.3 mm d⁻¹ in 2012. The ET₀ was generally higher early in the growing season than late in the growing season. From the sowing to the silking stage, the cumulative ET₀ was 371 mm in 2010, 408 mm in 2011 and 395 mm in 2012, accounting for 64, 69 and 68% of the total ET₀ over the whole growing season in 2010, 2011 and 2012, respectively (Fig. 1).

An analysis of daily precipitation indicated that dry spells occurred frequently in each of the three maize growing seasons (Table 1). The cumulative length of dry spells during the maize growing season was 114 d in 2010, 113 d in 2011 and 100 d in 2012, of which 56–62% occurred from sowing to silking. We assigned dry spells to one of four categories, according to duration. Within the four categories, the most common lengths were 5 d and 6–10 d, and they occurred five times before the silking stage over the three growing seasons. The 5-d and 6–10-d dry spells occurred three and five times after the silking stage, respectively, over the three
growing seasons. Dry periods of other lengths occurred less frequently. Dry spells 11–15 d in length occurred two times during the pre-silking stage and three times during the post-silking stage over the three growing seasons. A >15-d dry spell occurred one time during each growing season; the dates were 9–25 June in 2010, 30 May to 16 June in 2011 and 30 May to 17 June in 2012, when maize was in the jointing stage.

Table 1 Number of dry spells of varying lengths (days) during the pre- and post-silking stage in 2010, 2011 and 2012

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<th>Year</th>
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2.2. Soil water storage

Both the GM and FM treatments increased soil water storage (0–200 cm) during early growth compared with the non-mulching (CK) treatment. Compared with the CK treatment, the soil water storage at the 6-leaves stage (V6) was higher by 29, 41 and 15 mm for the GM treatment and by 52, 50 and 33 mm for the FM treatment in 2010, 2011 and 2012, respectively. From the V6 stage onward, soil water storage decreased in each treatment, and the between-treatment differences were reduced during maize growth. However, soil water storage increased in each treatment after the stage with lowest values. At the maturity stage (R6), no significant difference in soil water storage was observed among the CK, GM and FM treatments in any year (Fig. 2). Soil water storage at R6 increased 127–132 mm in 2010 and 89–136 mm in 2011 but decreased 16–25 mm in 2012 for the three treatments, compared with the values measured at the planting time (PT) (Fig. 3).

2.3. Evapotranspiration, maize yield and water use efficiency

The total evapotranspiration (ET) during the maize growing season ranged from 364 to 369 mm in 2010, from 351 to 396 mm in 2011 and from 379 to 389 mm in 2012; there was no statistically significant difference between treatments in
Each year, except for the GM treatment in 2011 (Table 2). However, the mulched treatments tended to increase ET during the pre-silking stage. As a result, the ratio of pre- and post-silking ET was significantly higher in the GM and FM treatments than it was in the CK treatment in the three study years, except for the GM treatment in 2010. In general, the FM treatment had a greater effect on the ratio of pre- to post-silking ET than the GM treatment. The correlation analysis showed that improving the soil water storage at sowing tended to increase ET during the pre-silking stage (Fig. 4). Compared with the CK treatment, both the GM and FM treatments significantly increased maize grain yield, with the greater effect observed in the FM treatment. The increases for the GM and FM treatments were 17.1 and 28.3% in 2010, 70.3 and 87.6% in 2011 and 16.7 and 38.2% in 2012, respectively (Table 3). In addition, the correlation analysis showed that the maize grain yield was positively correlated with the ratio between pre- and post-silking ET (Fig. 5).
2010 (496 mm) and 2011 (487 mm) were wet years, while 2012 (363 mm) was a severe dry year (Fig. 1). The ETs over the entire growing season in 2010 (364–369 mm) and 2011 (351–398 mm) were clearly less than seasonal rainfall but slightly higher by 16–26 mm than the seasonal rainfall in 2012 (Table 2). This finding indicates that maize production was not limited by the amount of rainfall in most years. Furthermore, if precipitation during the fallow season could be effectively harvested and utilized, plant water requirements in dry years would be satisfied. Our results are in agreement with those of previous studies (Barron et al. 2003; Hatibu et al. 2003; Barron and Kwacha 2005; Rockström et al. 2010), which reported that the production of most crops in semiarid areas is not constrained by the absolute amount of rainfall but by the irregular distribution of rainfall over time and the inefficient management of rainwater. This provides great opportunities for improving rainwater management to increase agricultural and water productivity in the vast semiarid regions.

During the growing season, dry spells result from temporally uneven rainfall distribution and usually induce crop failure (Rockström et al. 2010; Nyakudya and Stroosnijder 2011). Dry spells occurred frequently during the three years of this study, accounting for 70.9–73.1% of the maize growing periods (Fig. 1). Nevertheless, short-term dry spells had little impact on crop growth, whereas dry spells of ≥5–10 d were likely to damage maize growth (Barron et al. 2003; Stroosnijder 2007). In the three study years, growing-season dry spells of ≥5 d occurred six times in 2010, seven times in 2011 and five times in 2012 (Table 1). The frequent and long dry spells exposed maize plants to severe water stress during the period from sowing to silking (Table 1). In particular, the long dry spell of >15 d during the jointing stage postponed silking and shortened the grain filling period, adversely affecting final grain yield (Moser et al. 2006). Worse still, the high atmospheric evaporative demand during this period (Fig. 1) exacerbated the negative effects of dry spells. After the silking stage, although dry spells of ≥5 d still occurred (Table 1), the damage to the maize plants was alleviated by intensive rain events, increased rainfall and improved soil water storage (Figs. 1 and 2; Rockström et al. 2010; Nyakudya and Stroosnijder 2011). Other studies have also indicated that crop production on the Loess Plateau is primarily constrained by low rainfall between April and June (Liu et al. 2009; Zhang et al. 2013). Therefore, mitigating water deficit caused by long and frequent dry spells, particularly during the pre-silking stage, is the key to improving rainfed maize production in this semiarid region.

Previous studies have indicated that increasing rainwater harvest and conservation, improving water productivity and increasing plant water uptake capacity can mitigate water stress and optimize crop production (Kahinda et al. 2007; Rockström and Barron 2007; Rockström et al. 2010). In our study, the maize grain yields were significantly higher in the GM and FM treatments than in the CK treatment (Table 3). We suggest three possible explanations. First, both mulched treatments effectively captured the limited rainfall and retained it in the soil, thereby increasing soil water availability. Studies have reported that compared with the non-mulched plot, rainfall interception was approximately 12–15 times greater in the GM and FM mulched fields (Li et al. 2001, 2005); this would increase soil water storage sufficiently to provide a buffer during dry spells. In this study, higher soil water storage early in the growing season in the GM and FM treatments (Fig. 2) clearly promoted maize growth and development. As a result, maize plants reached the silking stage 3–8 days earlier in the GM treatment and 7–18 d earlier in the FM treatment (observed data), implying longer periods of grain filling and greater grain yields. Second, the two mulched treatments reduced nonproductive soil evaporation but increased productive plant transpiration.
Compared with the non-mulched soil surface, GM could reduce soil evaporation by 10–20% (Modaihsh et al. 1985; Groenevelt et al. 1989), and FM could lower soil evaporation by 24% (Li et al. 2013). In general, the total ET did not differ significantly among the three treatments (Table 2), implying higher plant transpiration in the GM and FM treatments. Thus, the plant physiological processes were enhanced, thereby improving water utilization (i.e., WUE) and grain yield (Table 3). Moreover, we found that both mulched treatments increased the ratio of pre- to post-silking ET (Table 2), which was positively correlated with yield improvement (Fig. 5). A similar result was found in other studies of maize on the Loess Plateau (Zhang et al. 2014). However, Zhang et al. (2013) reported that wheat yield positively responded to the ratio between post- and pre-anthesis ET on the Loess Plateau, primarily because the dry spells between May and June usually constrained wheat grain filling. These results demonstrated that ensuring water supply and crop water use during the dry season is most important for increasing grain yield. Third, both mulched treatments most likely promoted maize root growth (Maurya and Lal 1981; Xie et al. 2006). A dense root system is essential for stimulating plant water uptake and, consequently, increasing water utilization (Rockström and Barron 2007).

Notably, crop yield does not depend solely on water supply during the growing season (via precipitation and/or irrigation), but it is also closely related to soil water storage at sowing (Musick et al. 1994). Except for the CK treatment in 2011, grain yields showed no significant difference (P > 0.05) among the 3 yr for each treatment (Table 3), though the rainfall in 2012 was dramatically lower than those in 2010 and 2011 (Fig. 1). This is mainly because the high soil water storage at sowing in 2012 (Fig. 2) ensured an adequate soil water supply and plant water availability, especially during the pre-silking stage (Table 2 and Fig. 4). This result indicated that excess rain in wet years could be retained in the soil to be used the next year (Fig. 3), which is particularly important for dry years. Additionally, the mulching gravel and plastic film should be left in the field after harvest to capture rainfall and reduce soil evaporation during the fallow season.

4. Conclusion

This study found that temporally uneven rainfall distribution, resulting in soil water stress (especially during the pre-silking stage), was the major constraint on maize growth and development in the area. GM and FM clearly increased soil water storage and ensured plant water availability, particularly during the early growth seasons; this mitigated the negative impacts of water deficit and improved water utilization. Consequently, both mulched treatments significantly increased the maize yield. However, FM was more effective than GM in improving grain yield. These results may provide valuable information for improving agricultural production and water utilization in semiarid areas.

5. Materials and methods

5.1. Site description

The field study was conducted from 2010 to 2012 at the Changwu Agricultural and Ecological Experimental Station (35.28°N and 107.88°E at an altitude of 1200 m above sea level), located on the semiarid Loess Plateau in northwest China. The average annual precipitation from 1957 to 2009 was 582 mm, with 426 and 312 mm falling between May and September (i.e., maize growth season) and between July and September (maize silking usually occurs in the middle of July), respectively. The annual evaporation from a free water surface is 1565 mm, and the mean annual temperature is 9.7°C. Rainfed agriculture is dominated by monoculture cropping systems that produce one crop of maize or wheat per year across the region. According to the Chinese Soil Taxonomy, the soils at this site are Cumuli-Ustic Isohumosols (Gong et al. 2007). The top 20 cm of soil had a pH of 8.4 and a bulk density of 1.3 g cm–1 and contained 16.4 g kg–1 organic matter, 1.05 g kg–1 total N, 0.70 mg kg–1 available phosphorus (Olsen-P), 133.1 mg kg–1 available potassium (NH₄OAc-K) and 28.8 mg kg–1 mineral N.

5.2. Experimental design and treatments

Three treatments were applied to maize fields for 3 yr. The treatments were a control with non-mulching (CK), gravel mulching (GM) and plastic film mulching (FM). A planting pattern of alternating wide (60 cm) and narrow (40 cm) row spacing was used for each treatment. The CK treatment was a flat non-mulched field, the GM treatment was mulched with 5–6 cm thick gravel (2–4 cm in diameter), and the FM treatment was mulched with a piece of transparent plastic film (0.008 mm in thick) laid over the plot. Each treatment was replicated three times in 56 m² plots (7 m×8 m) in a randomized complete block design. In 2011 and 2012, each plot was at the same site as in 2010; the gravel and plastic film were both replaced in the latter two years.

After ridging treatment plots, chemical fertilizers at rates of 90 kg N ha–1 in the form of urea (N 46%), 40 kg P ha–1 in the form of calcium superphosphate (P₂O₅ 12%) and 80 kg K ha–1 in the form of potassium sulfate (K₂O 45%) were manually broadcast over the soil surface; the soil was then plowed to drive the fertilizer to the subsoil. Additionally, all plots were topdressed twice each with 67.5 kg N ha–1...
(urea, N 46%) at the jointing and silking stages using a hole-sowing machine.

In each plot, maize (Pioneer 335) was planted at a density of 65 000 plants ha⁻¹ at a depth of 5 cm. Planting was done with a hand-powered hole-sowing machine on 28, 28 and 21 April in 2010, 2011 and 2012, respectively. During the growing season, natural rainfall was the only water source. Maize cobs were harvested when they were ripe, gradually from 20 to 26 September in 2010 and on 25 September in 2011. In 2012, all treatments were harvested earlier, on 7 September, because of lodging.

5.3. Sampling and analysis

Soil samples were collected at planting time (PT), 6-leaf stage (V6), 10-leaf stage (V10, in 2011 and 2012), 12-leaf stage (V12, only in 2010), silking stage (R1), milk stage (R3), dent stage (R5) and physiological maturity stage (R6). For each sample, a soil auger was used to collect cores to a depth of 200 cm at 20-cm intervals in each plot. Soil water content was determined gravimetrically by oven-drying the core samples at 105°C for 24 h.

At harvest, all plants from an area of 10 m² (4 rows each 2.5 m long) in the middle of each plot were manually harvested to determine grain yield, which was adjusted to 15.5% moisture.

5.4. Calculations

Dry spell In this study, the method described by Stern et al. (1982) was used to identify dry spells based on daily rainfall data, i.e., a dry day is a day with rainfall <0.85 mm, and a dry spell is any consecutive number of dry days.

Soil water storage, evapotranspiration and WUE Soil water storage (W) in the profile was considered to be the total storage in all sampled layers in the plot and was calculated using the following formula: \( W = h \times \rho \times \theta \times 10 \), where \( h \) is soil depth (cm), \( \rho \) is soil bulk density (g cm⁻³) and \( \theta \) is soil water content (%) in the corresponding soil layer.

Evapotranspiration (ET) during the maize growth season was calculated according to the following formula: \( ET = \Delta W + P \), where \( \Delta W \) is the change in soil water storage (mm) in the 0–200 cm profile between planting and harvest and \( P \) is the precipitation (mm) during the growth season.

The reference evapotranspiration (\( ET_0 \)) was estimated using the FAO Penman-Monteith equation (Allen et al. 1998) to assess the atmospheric evaporative demand of the atmosphere. The input data were obtained from an automatic weather station approximately 50 m from our experimental field.

WUE was calculated as the grain yield (kg ha⁻¹) divided by total ET (mm) over the maize growing season.

5.5. Statistical analyses

The effects of the treatments on the measured parameters were evaluated using a one-way ANOVA. When the \( F \)-values were significant, the least significant difference (LSD) test was used to compare means. In all cases, differences were deemed to be significant at \( P<0.05 \).

Acknowledgements

This research was financially supported by the National Natural Science Foundation of China (31270553), the National Basic Research Program of China (2009CB118604) and the Special Fund for Agro-Scientific Research in the Public Interest of China (201103003).

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