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Effects of tillage and plastic mulch on soil water, growth and yield of spring-sown maize

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ABSTRACT

The large dryland area of the Loess Plateau is subject of developing strategies for a sustainable crop production, e.g. by modifications of field management affecting soil water status and crop productivity. A three-year field experiment was conducted to investigate the effects of field management practices on soil water, maize development and yield on the Loess Plateau of China. The field management practices included traditional tillage (CK), no-till with crop residue mulch (SM), alternating ridges mulched with plastic film and bare furrows (PM) and alternating ridges mulched with plastic film and furrows mulched with crop residue (PSM). The soil water storage was higher under SM than the other treatments, except in the first half of the first maize growing season. Higher soil water stimulated maize growth, as indicated by a higher leaf area index and greater biomass accumulation, and thus the highest grain yield (7251 kg ha^{-1}) and water use efficiency (2.41 kg m^{-3}) in the first experimental season was recorded in SM plots. Maize growth and grain yield did not benefit in the other two seasons. Although soil water storage was similar between PM or PSM and CK treatments at sowing and harvest time, consistently better maize development and higher grain yield were observed through three seasons in PM and PSM plots. Under the PM and PSM treatments grain yield was 8–24% and 13–24% higher, respectively, than under the CK treatment, indicating that utilization of water and other resources was better under these treatments. However, significant soil water depletion in deeper (>100 cm) soil layers was detected at harvest time under PM compared with CK, implying that higher yields might not be sustained in the long run. In conclusion, crop residue mulching combined with no-tillage is not recommended for spring-sown maize system under these temperate climate conditions. Instead, use of ridges mulched with plastic film combined with crop residues in furrows may be an efficient measure to increase crop yield and maintain or improve soil fertility.

1. Introduction

The Loess Plateau has a cropland area of 16 million ha, and the climate is mostly semiarid, with annual precipitation ranging from 200 mm to 600 mm (Li and Xiao, 1992). Dryland farming in the Loess Plateau is dominated by monoculture cropping systems, with mainly spring maize (*Zea mays* L.), winter wheat (*Triticum aestivum* L.) and spring potato (*Solanum tuberosum* L.). Crop production in this dryland region is constrained by water deficiency, and soil erosion caused by wind and/or water. Conventional tillage practices, including intensive soil cultivation and crop residue removal and burning, have exacerbated soil erosion and degradation, thus contributing to the development of soils with low organic matter contents and a fragile physical structure (Bi, 1995; Tang, 2004). In attempts to control the severe erosion and ensure the food security of local people, conservation tillage has been encouraged as a means of conserving soil and water resources and increasing crop yields. However, the effectiveness of conservation tillage on soil water storage and crop yield depends on the soil type, climate, and land types (Tolk et al., 1999; Lampurlanes et al., 2002; Zhang et al., 2009). Xie et al. (2008), reviewing available research, reported that conservation tillage increased crop yield or gave similar yields to conventional tillage according to 89% of studies over the past decade in China, and decreased crop yields according to about 11% of studies. Nevertheless, under conservation tillage less energy input, soil water conservation, improvement of soil quality and other ecological benefit (e.g. control of soil erosion) could be achieved (Blanco-Canqui and Lal, 2008; Govaerts et al., 2009; Li et al., 2009; Morris et al., 2010).

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On the Loess Plateau, other field management practices, such as mulching with plastic film, have been extensively applied to crop production. Practices include alternating ridges and furrows, with only the ridges mulched with plastic film (Li et al., 2001; Wang et al., 2009), alternating mulched and bare rows without ridges (Liu et al., 1989), and a recently developed technique of double ridges and furrows mulched with plastic film. The last of these patterns reportedly improves yield significantly (Liu et al., 2009; Zhou et al., 2009), and it has recently been widely adopted in the northwest of the Loess Plateau. However, the sustainability of rain-fed agro-ecosystems may be impaired by the use of non-degradable plastic film and the prevention of crop residues returning over many years. These techniques may accelerate the decomposition of soil organic matter, change the soil structure, and influence root development (Li et al., 2007). Furthermore, the large quantities of plastic film used with double ridges may also cause pollution (Shah et al., 2008). It is, therefore, necessary to evaluate the feasibility of alternative field management practices to guarantee both food security and system sustainability. However, information is scanty on the comparative effects of various mulching practices with the same crop under similar type of agro-environment. In this context, we explored the effects of crop straw mulching under no-tillage, ridges mulched with plastic film combined with furrows covered with or without crop residue on spring-sown maize system. We hypothesized that (i) soil water storage and its distribution in soil profile would differ with various mulching practices, and (ii) maize development and yield and water use efficiency would also be affected.

2. Material and methods

2.1. Site description and experimental design

The field study was conducted from 2007 to 2009 at a site on the Loess Plateau (35.14N, 107.41E and 1206 m above sea level) in Changwu county of Shaanxi Province, China. The average annual precipitation of the site is 578 mm, with 55% falling between July and September and the annual average temperature is 9.3 °C. The water table is at a depth of more than 60 m and thus, groundwater is unavailable for plant growth. The soil at the study site had a silt loam texture according to the USDA texture classification system. Soil organic carbon content, total nitrogen, available phosphorus, available potassium and bulk density at 0–20 cm depth were 6.92 g kg^{-1}, 0.47 g kg^{-1}, 28 mg kg^{-1}, 96 mg kg^{-1}, and 1.21 g cm^{-3}, respectively.

In this experiment, four treatments were designed and applied: (1) a flat plot with no mulching (CK), (2) straw mulching with 4500 kg/ha wheat straw in the first season and maize stalks in other seasons (SM), (3) alternating ridges (60 cm wide and 15 cm high) and furrows (60 cm wide) with only the ridges mulched with white plastic film (PM), and (4) alternating ridges (60 cm wide and 15 cm high) and furrows (60 cm wide) with the ridges mulched with white plastic film and straw mulching in the furrows (2250 kg/ha) (PSM). A sketch showing the ridge and furrow system is presented in Fig. 1. Each treatment was replicated four times and each plot was 8 m long and 8 m wide in a randomized block arrangement. The entire experimental area was ploughed before the plots were marked out in 2007. After ridging treatment plots, fertilizers at rates of 150 kg N ha^{-1} and 35 kg P_2O_5 ha^{-1} were incorporated into the soil by spade (across the whole plot for treatments CK and SM, and into the furrows for treatments PM and PSM). Maize was planted with a row space of 60 cm (two rows in each furrow at the base of the ridges) and in all treatments at a density of 54,000 plants ha^{-1}. The maize cultivar "Shendan 10" was sown on 12 April 2007, 18 April 2008 and 16 April 2009, using a hole-sowing tool. The plots were harvested on 15 September 2007, 16 September 2008 and 17 September 2009. After maize harvest, in all plots except SM plots, the plastic film was cleared, maize stalks were removed and then plots were ploughed by spade (dug over) at the end of October or early November (the mulched straw or stalks were incorporated into soil at the same time in the PSM treatment). Other sowing activities were the same as those in 2007. In the SM plots, ca. 20 cm high maize stubble was left without any tillage. During the subsequent sowing operation, straw was removed temporarily, weighed, then fertilizers were applied by making a trench beside each planting row, and finally straw was returned at the rate initially used. In addition, straw mulch was applied at the three-leaf maize stage every experimental season in the PSM treatment, and in 2007 in the SM treatment.

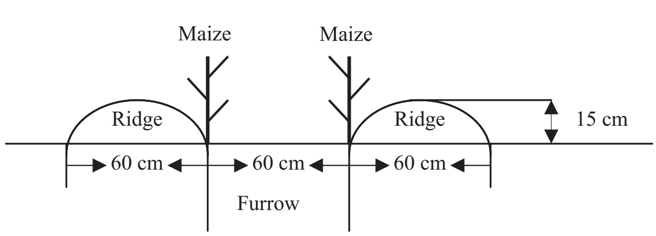

Fig. 1. A sketch of the ridge and furrow system.

2.2. Sampling and measurements

Plants were sampled approximately monthly for leaf area and biomass determinations. Initially, five plants and subsequently three plants were sampled randomly from each plot, located at least 1 m from plot edges and 0.5 m from previous sampling sites. Shoots were cut at ground level, and leaf area was assessed by multiplying leaf length by the greatest width and applying a correction factor (0.75) according to McKee (1964). The sum of total green leaf area was used to determine LAI, based on the number of plants in the plot. Total above ground biomass was determined gravimetrically after oven drying, at 105 °C for 30 min initially and then at 65–75 °C for 48 h.

Before maize sowing, neutron probe tubes were installed in three replicate plots of each treatment, positioned in the middle of furrows for PM and PSM treatments. The water content in the soil profile was determined at depth intervals of 10 cm, down to 100 cm, and at 20 cm intervals from 100 to 200 cm. Measurements were made approximately every two weeks during the maize growing season and have continued since the start of the experiment. Soil water contents in the upper 20 cm of soil were determined by the gravimetric method, at the same time as taking neutron probe readings. Soil water storage (W) in the profile was considered to be the total storage in all of the sampled layers in the plot. Evapotranspiration (ET) was determined using the formula ET = $P - \Delta W$, where P is the precipitation (mm) during the crop growth season and ΔW is the change in soil water storage (mm), without considering deep percolation and runoff. Water use efficiency (WUE) was calculated as grain yield (GY) in kg m^{-2} divided by total water use in m (evaluated as ET in the present study), i.e., WUE = GY/ET.

2.3. Statistical analyses

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

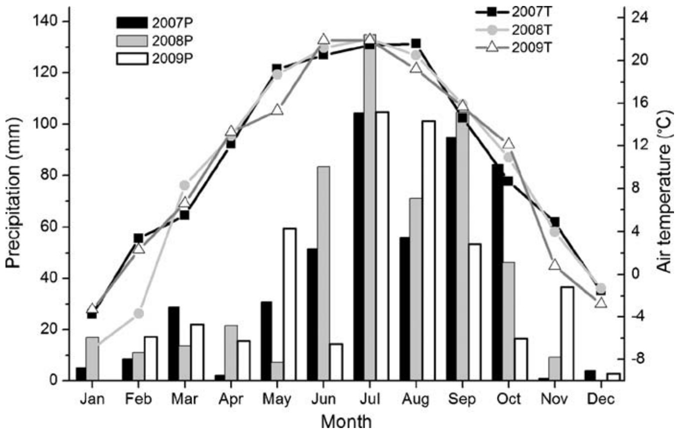

Fig. 2. Distribution of monthly precipitation and air temperature from January 2007 to December 2009.

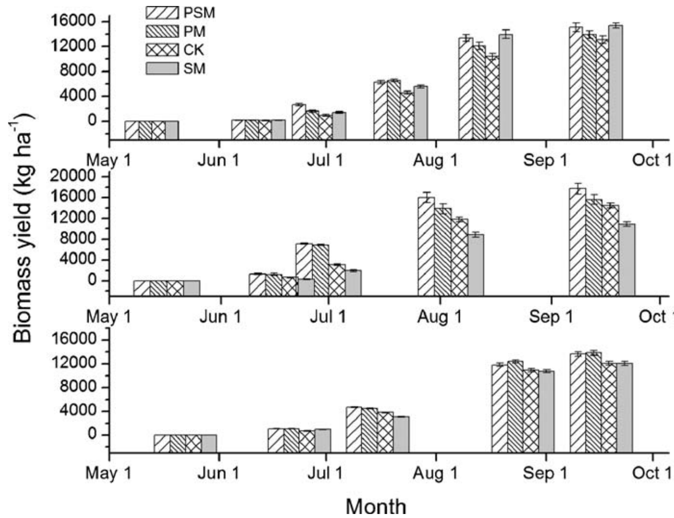

Fig. 4. Changes in maize biomass under CK, SM, PM and PSM treatments in three maize growing seasons: 2007 (up panel), 2008 (middle panel) and 2009 (bottom panel). Bars show standard errors.

3. Results

3.1. Weather conditions

Rainfall during the spring maize growing season amounted to 302 mm in 2007, 340 mm in 2008 and 343 mm in 2009 (Fig. 2), accounting for 64%, 65.2% and 71.3% of annual precipitation, respectively. The first growing season was drier than the other two seasons. Nevertheless, rainfall distribution varied from season to season, e.g. much more rain fell in June and July 2008 than in these months of 2007 and 2009, and considerably less fell in June and more in August 2009 than in corresponding months of 2007 and 2008.

Air temperature also varied greatly between the three experimental seasons (Fig. 2). There were significantly lower temperatures in May and August 2009 than in those months of 2007 and 2008. The differences in rainfall and air temperature between experimental seasons would be expected to affect maize development and cause variations in yield.

3.2. Maize leaf area index (LAI) and shoot biomass

Generally, LAI of maize was lowest in 2007, highest in 2008 and intermediate in 2009. In 2007, LAI was higher under PM and PSM than under SM and CK during the early stages of maize development. LAI was significantly higher at the fourth and fifth sampling dates on PSM plots, compared with PM and CK plots (Fig. 3). However, LAI was significantly higher on SM plots than those of other treatments at the fifth and sixth sampling dates, and reached peak values later than under other treatments. LAI was significantly lower at the last two sampling dates on CK plots than those of other treatments. In 2008 and 2009, the patterns of LAI variations were similar, LAI being consistently and significantly higher on PM and PSM plots than on SM and CK plots. However, at harvest time LAI was significantly lower on PM plots, compared with PSM plots.

The changes in shoot biomass were similar to those of LAI during the three experimental years (Fig. 4). The shoot biomass accumulated faster under PM and PSM treatments than under SM and CK treatments during the early stages of maize development in all three experimental years. It was also consistently and significantly greater on PM and PSM plots than on SM and CK plots in 2008 and 2009, during the whole growing season. However, in 2007, shoot biomass was higher on the SM plots than on the other treatment plots at the last two sampling dates.

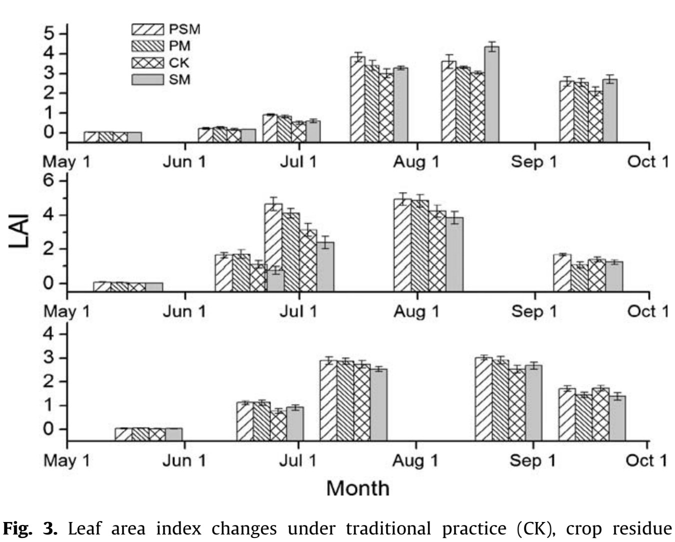

Fig. 3. Leaf area index changes under traditional practice (CK), crop residue mulching (SM), ridges and furrows, with ridges mulched with plastic film (PM), and ridges and furrows, with ridges mulched with plastic film and furrows mulched with crop residues (PSM) in three maize growing seasons: 2007 (up panel), 2008 (middle panel) and 2009 (bottom panel). Bars show standard errors.

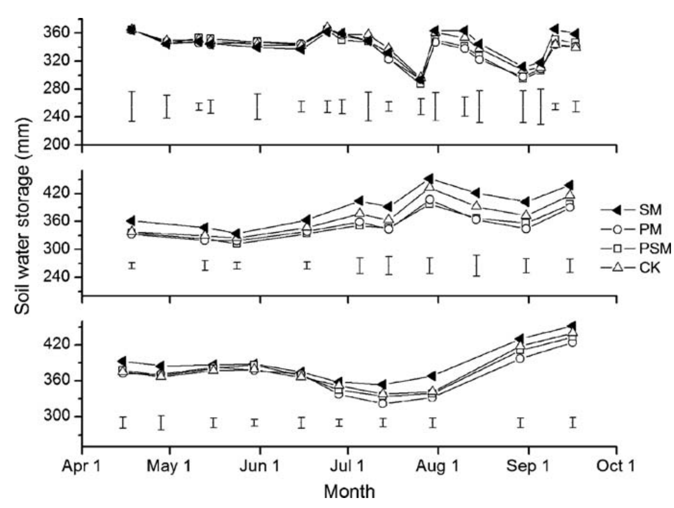

Fig. 5. Changes in soil water storage (0–200 cm) under CK, SM, PM and PSM treatments in three maize growing seasons: 2007 (left panel), 2008 (middle panel) and 2009 (right panel). Bars show $LSD_{0.05}$ values.

These findings are consistent with the observations of LAI dynamics.

3.3. Soil water

The soil water storage (SWS) dynamics (0–200 cm) showed substantially different patterns in the three experimental seasons (Fig. 5). In the first season, SWS was depleted within the maize growing season, with low values in late July and the end of August, and the difference in SWS between sowing and harvest was small. In the second season, SWS generally increased up to maize harvest. In the third season, SWS was decreased from sowing until the middle of July, when it fell to its lowest value, then increased up to harvest time. In 2007, SWS was similar for all treatments from sowing to the end of July. After that time, differences between treatments appeared; SWS was subsequently highest under SM, and lowest under PM and PSM. Nevertheless, there were no significant differences between treatments in this respect, except at the last two sampling dates, when SWS was significantly higher under SM than under CK and PM. In 2008 and 2009, SM significantly improved SWS at planting time, compared with other treatments, and the trend continued throughout the whole growing season. However, SWS was mostly lowest under PM as maize development progressed.

The soil water contents in the profile at harvest under all treatments reflected significant depletion of soil water in deep soil layers, relative to those prior to sowing in the first experimental season (2007) (Fig. 6). The SM treatment significantly increased the soil water content in the upper 80 cm soil layer, compared with the CK and PM treatments, while at other depths no significant differences were observed between treatments, consequently, 20–29 mm more water was stored under SM than under other treatments. The soil water contents were significantly higher under SM than other treatments at sowing time in nearly all measured layers in 2008 (Fig. 7), yielding 18–25 mm more water than other treatments. No significant differences in this respect were observed between CK, PM and PSM treatments. After maize harvest in 2008, soil water contents were almost similar down to 60 cm for all treatments. However, PM plots had significantly lower water contents than CK, SM and PSM plots at depths from 100 cm to 120 cm. At depths from 140 cm to 200 cm, PM and PSM plots had markedly lower water contents than CK and SM plots. At sowing time in 2009, SM plots had significantly higher water contents in upper and lower layers than those subjected to other treatments, though no significant differences among treatments

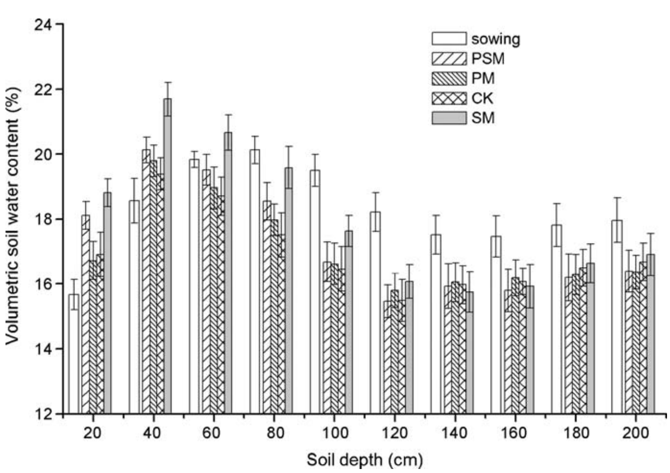

Fig. 6. Soil water contents at maize sowing and harvest time under CK, SM, PM and PSM treatments in 2007. Bars show standard errors.

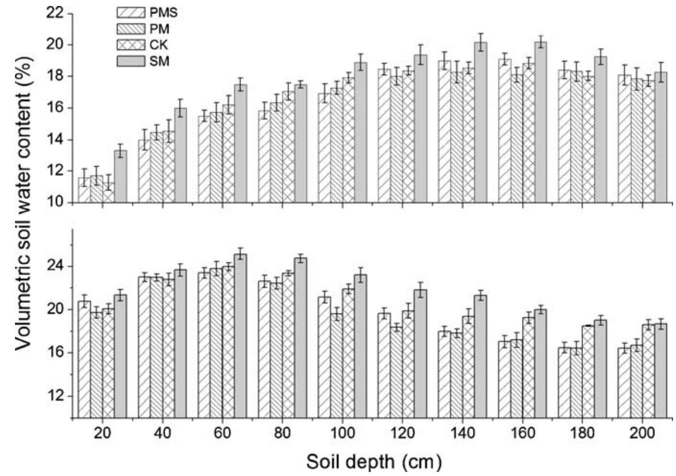

Fig. 7. Soil water contents at maize sowing (top panel) and harvest time (bottom panel) under CK, SM, PM and PSM treatments in 2008. Bars show standard errors.

were detected from 60 down to 140 cm depth (Fig. 8). At harvest time, soil water contents were significantly lower under PM and PSM than under CK and SM, at soil depths from 120 to 160 cm.

3.4. Maize yield, water use and water use efficiency

Maize yield varied between the three experimental seasons, with the highest yields recorded in 2008 and the lowest in 2009 (Table 1). In 2007, maize yields of PM, PSM and SM plots were similar and significantly higher than those of CK plots. However, the yield was significantly lower under SM than under other treatments, and significantly higher under PSM than under other treatments, in 2008. In 2009, maize yields of PM and PSM plots were similar and significantly higher than those of CK and SM plots (which were not significantly different from each other).

In 2007, evapotranspiration (ET) of maize was significantly lower under SM than under CK and PM, while ET values for PSM did not significantly differ from those of any of the other treatments (Table 1). In 2009, ET was similar for all treatments.

The SM treatment significantly increased WUE compared with the CK treatment in 2007, there were no differences between SM and PM and PSM treatments in this respect, nor between CK and PM or PSM treatments (Table 1). In 2008, WUE was highest under PSM, and significantly higher than under the other treatments

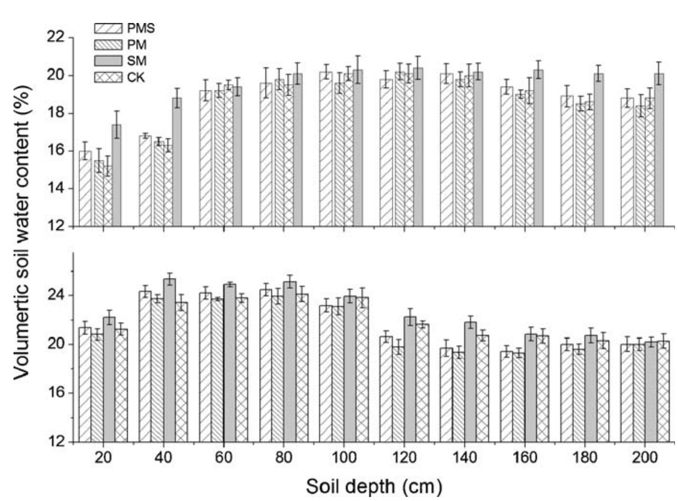

Fig. 8. Soil water contents at maize sowing (top panel) and harvest time (bottom panel) under CK, SM, PM and PSM treatments in 2009. Bars show standard errors.

Table 1
Maize grain yield, evapotranspiration (ET) and water use efficiency (WUE) under traditional practice (CK), crop residue mulching (SM), ridges and furrows, with ridges mulched with plastic film (PM), and ridges and furrows, with ridges mulched with plastic film and furrows mulched with crop residue (PSM).

Treatments	Grain (kg ha^{-1})			ET (mm)			WUE (kg ha^{-1}mm^{-1})		
	2007	2008	2009	2007	2008	2009	2007	2008	2009
CK	6371b	7063c	4100b	330a	261b	278a	19.3b	27.1b	14.7b
SM	7251a	5155d	4301b	301b	263ab	281a	24.1a	19.6c	15.3b
PM	6973a	7658b	5106a	329a	282a	289a	21.2a	27.1b	17.7a
PSM	7196a	8742a	4983a	321ab	277ab	286a	22.4a	31.5a	17.4a

Numbers in each column followed by different letters indicate significant ($P \leq 0.05$) differences between treatments according to LSD tests.

(similar to the observed treatment effects on maize yield). WUE was lowest under SM, and significantly lower than under PM and CK. In 2009, WUE was similar for all treatments.

4. Discussion

Field management practices affect soil surface conditions and influence soil water and thermal status, which play an important role in crop development and growth in dryland farming. Crop residue mulching can significantly reduce soil evaporation (Steiner, 1989), improve soil water storage (Zhang et al., 2007) and reduce soil temperatures in spring and summer (Ma and Xu, 1998; Zhang et al., 2009). The observed variations in LAI and shoot biomass during the three experimental seasons under SM in the present study were presumably related to variations in soil water and soil thermal conditions although sol temperature was not measured in this experiment. In 2007, the experimental area was ploughed before sowing and straw mulching was applied at the three-leaf stage, and may have had minor negative effects on soil temperature, but conserved more water later and hence stimulated maize growth. The LAI and shoot biomass were, therefore, higher on SM plots than on other plots in the late stages of maize development (Figs. 3 and 4). This resulted in the grain yield and WUE being highest under SM in 2007 (Table 1). However, in 2008 and 2009, higher soil water storage at sowing and throughout the seasons under SM plots did not enhance maize development and growth, moreover, no special diseases or pests were detected in the SM plots. This might have been due to the greater amount of water under the no-tillage and the surface cover of crop residues on SM plots, which may have slowed the rise of soil temperature (Davies et al., 1993; Licht and Al-Kaisi, 2005; Ma and Xu, 1998) and delayed maize development and growth. Grain yield and WUE was generally low on SM plots. Similar results have been reported elsewhere (Ma and Xu, 1998; Gao and Li, 2005; Cook et al., 2006). The results indicate that crop residue mulching under no-tillage is not beneficial in the temperate climate conditions in the study area, it might be useful under conventional tillage as in the first season since it may then improve crop productivity by reducing the effects of adverse thermal conditions and enhancing water conservation. In addition, one maize cultivar was planted in present study; the responses of different varieties to the SM practice might be different. Further investigations are, therefore, worth to study when SM application is suitable and the responses of various cultivars under SM practice.

Consistently higher grain yield and WUE were recorded under the PM and PSM treatments than under the CK treatment over the three seasons, probably because mulching with plastic film increased soil temperature (Anikwe et al., 2007; Li et al., 2001) and radiation capture (Liu et al., 2010), and augmented available soil water (Anikwe et al., 2007; Liu et al., 2010), thus enhancing growth of the maize, as indicated by higher LAI and shoot biomass (Figs. 3 and 4). These findings are consistent with those of other studies (Li et al., 2001; Wang et al., 2009). However, we found significant soil water depletion in deeper soil layers, especially under PM at harvest time in 2008 and 2009 (Figs. 7 and 8). The organic carbon content in the 0–10 cm soil profile was significantly lower under PM than under other treatments after three growing seasons (data not shown). Similarly, Li et al. (2007) found that mulching with plastic film accelerated decomposition of soil organic matter during non-flooded rice cultivation. These observations imply that the PM system might deplete soil fertility and soil water rapidly, and hence fail to sustain crop production in the long run. In comparison with PM, the PSM treatment could ameliorate soil water depletion in the soil profile and tended to increase soil organic carbon content (data not shown) in the plough layer, due to incorporation of mulched crop residues after maize harvest. Hence, use of ridges mulched with plastic film combined with furrows covered with crop residue could be recommended as an efficient means of increasing crop yield and maintaining or improving soil fertility. However, in view of the potential for pollution by plastic films and the improvement of soil organic carbon content, further studies are needed to investigate the maximum area that should be covered by crop residue mulching and the least area that should be covered by plastic film mulching to optimise both thermal and water regimes for crop growth.

5. Conclusions

Analysis of the results from the three years experiment has shown that straw mulching combined with no-tillage played a significant role in increasing soil water storage, but resulted in poor maize development and grain yield possibly due to unsuitable thermal conditions at sowing and early stage of maize development. The ridges mulched with plastic film combined with furrows covered with or without crop residue promoted maize growth and thus the more consumption of soil water and led to lower soil water storage, but enhanced maize development and grain yield and water use efficiency. Whereas, it should be aware that the ridges mulched with plastic film combined with bare furrows had a tendency of depleting soil water at deeper layers. Hence, the combination of plastic film mulched ridges with crop residue covered furrows could be a better field-management option for spring-sown maize system under the temperate climate condition.

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