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Improved yield by harvesting water with ridges and subgrooves using buried and surface plastic mulchs in a semiarid area of China

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ABSTRACT

This paper determines the responses of soil temperature, water status and crop yields to a new planting pattern involving ridges and subgrooves with plastic film mulching in a millet-field pea-spring wheat-potato cropping system. The study was conducted in a typical semiarid area, during the four annual growing seasons of 2005–2008 and five treatments were designed: (1) a flat plot with no mulching, which is the conventional tillage practice (CK); (2) alternating ridges and furrows with no mulching (M0C0); (3) alternating ridges and furrows with no mulching, and subgrooves mulched with plastic film (M0C); (4) alternating ridges and furrows, with only the ridges mulched with plastic film on the surface (MC0); and (5) alternating ridges and furrows, as well as subgrooves, with the ridges and subgrooves mulched with plastic film (MC). The subgrooves with plastic film mulching increased topsoil temperature, the average daily soil temperature of the 4-growing seasons was 16.7, 16.8, 16.9, 17.4 and 17.2 °C for the CK, M0C0, MC0, M0C and MC, respectively. The soil temperature was significantly higher in the M0C and MC than in the CK, M0C0 and MC0 in May 2006, September in 2007 and May 2008. In average and wet years, the soil water content in the 20–40 cm soil layer was 6.2–37.7% higher in the MC than in the CK. The ridges and subgrooves with plastic film mulching improved crop yields, and the average yield over the four years was higher in the MC than in the CK, M0C0, M0C and MC0 by 163%, 98%, 62% and 21%, respectively. Potato is a staple and economic crop in this region, and the ratio of large and moderate-sized potato tuber yield to total tuber yield was 21.7% higher in the treatments with subgrooves than in the treatments without subgrooves. In conclusion, the technique of ridges and subgrooves with plastic film mulching is an effective practice for improving crop yields in semiarid agroecosystems.

1. Introduction

Precipitation is the main water resource affecting crop production in semiarid areas (Gan et al., 2013; Xiao et al., 2013; Nyakudya et al., 2014). In these regions, low intensity and unpredictable precipitation, and high evaporation always severely limit crop yields (Turner, 2004; Zhou et al., 2009; Liu et al., 2013a). Agricultural production in these regions depends on precipitation, and farmers are concerned about the optimized water use. The highly effective use of precipitation is a key priority in guaranteeing food security and sustainability. The Loess Plateau of northwestern China is characterized by a semiarid monsoon climate, where no water resources are available for agriculture irrigation. From the 1960s–1990s, in order to reduce runoff and soil erosion and increase the rainfall use efficiency in this region, a large number of terraced fields and silt-retention dams were built (Zheng, 2003; Lu et al., 2006; Yang, 2006; Chen et al., 2007). Although terraced fields and silt-retention dams increase the crops water use efficiency, they need significant inputs of much money and labor. Since the 1990s many more cheaper and effective technologies, including plastic film mulching and rainwater harvesting, have been widely applied in semiarid agroecosystems (Wang et al., 2005; Jia et al., 2006; Zhou et al., 2009; Liu et al., 2009, 2014; Zhao et al., 2014). In particular, ridge-furrow rainwater harvesting with plastic film has proven to be one of the most

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effective methods to increase crop yields and water use efficiency (WUE), which it does by means of collecting water from light rain, retaining the surface runoff from heavy rain, and reducing evaporation, and compared to the conventional tillage practice, the maize and potato yields in the ridge-furrow with plastic film mulching increased by 28–90% and 57–78%, respectively, and the corresponding WUE increased by 26–88% and 62–70%, respectively (Bu et al., 2013; Gao et al., 2014; Zhao et al., 2014).

In the semiarid regions of China, the major shallow-root crops including Millet (*Setaria italica* L.), field pea (*Pisum sativum* L.), spring wheat (T*riticum aestivum* L.) and potato (*Solanum tuberosum* L.) (Xiao et al., 2007; Wang et al., 2008; Duan et al., 2013). The soil water and nutrient contents in the top soil layers are crucial for the growth of shallow-root crops (Ju et al., 2006; Liu et al., 2013a). Existing studies have mainly been aimed at the effects of ridge-furrow rainwater harvesting with plastic film on these crop yields and WUE. The new tillage practice of harvesting water with ridges and subgrooves which are plastic films that are buried 40 cm below the soil surface has been recently introduced into rainfed farming systems on the Loess Plateau of China, which significantly increased spring wheat yield by improving the soil water content and temperature in the topsoil of the subgrooves (Lin et al., 2006).

However, currently the response of crop yields to ridges and subgrooves with plastic film mulching remains unknown. Much work in this area remains to be done, therefore the objectives of this study are to investigate the influence of the ridges and subgrooves with plastic film mulching on soil temperature, soil water retention and crop yields in a semiarid area.

2. Materials and methods

2.1. Description of study site

The field experiment was conducted from July 2005 to August 2008, at the Semiarid Ecosystem Research Station of the Loess Plateau (36°02′N, 104°25′E, 2400 m above sea level), Lanzhou University, Gansu Province, China. The study area is located at Zhong-Lian-Chuan in the northern mountainous region of Yuzhong County, Gansu Province. The area has a medium temperate semiarid climate, with an annual mean air temperature of 6.5 °C, a maximum of 19.0 °C (July), and minimum of −8.0 °C (January). The mean annual precipitation is 320 mm, about 60% of which falls in July–September, and the average annual free water evaporation is about 1300 mm. Rainfall during the experimental period was measured using an automatic weather station (WS-STD1, England). The water table is very deep, thus groundwater is unavailable for plant growth. The soil is Heima soil (Calcic Kastanozem, FAO Taxonomy), with the water content of 22.9% at field capacity (gravimetric) and a permanent wilting point of 6.2% (Shi et al., 2003). In the 0–20 cm soil layer, soil sand (>50 μm), silt (2–50 μm) and clay (<2 μm) is 17.7%, 82.1% and 0.2%, respectively, and water-stable aggregation size >2.0 mm, 2.0–1.0 mm, 1.0–0.25 mm and <0.25 mm is 3.0%, 3.5%, 21.4% and 72.1%, respectively. In this region, the major land use form was cropland, other land use systems, including pasture and plantations (Liu et al., 2010).

2.2. Experimental design and field management

In this experiment, we applied five treatments: (1) a flat plot with no mulching (CK); (2) alternating ridges and furrows with no mulching (M0C0); (3) alternating ridges and furrows with no mulching, with the subgrooves mulched with plastic film (M0C); (4) alternating ridges and furrows, with only the ridges mulched with plastic film (MC0); (5) alternating ridges, furrows and subgrooves, the ridges and subgrooves mulched with plastic film (MC). A sketch showing different treatments is presented in Fig. 1. The design of the soil subgrooves in M0C and MC treatments was as follows: the subgrooves were 2 m long, 0.5 m wide and 0.4 m high; the soil in the subgroove was removed; the walls and bottoms of the subgrooves were mulched with plastic film (0.03 mm); and the soil was back filled in the subgrooves. The white plastic film mulched on the ridges is 0.0075 mm thick. In the ridges and subgrooves system, crops were planted in the furrows between the two ridges, and the subgroove basically acted as a barrier for deep percolation that holds water in the root zone. Each treatment was replicated three times, and each plot was 3 m long and 2 m wide, placed in a randomized block arrangement. In this study, the big agriculture farming machine could be applied because of the relatively small fields, and the ridges and subgrooves were built with a spade. Bare ridges were made between every second plot to prevent runoff. According to local fertility practices, fertilizers at the rates of 105 kg N ha^{-1}, 12 kg P ha^{-1} and 25 kg K ha^{-1} for crops in each year were incorporated into the soil by spade (across the entire plot for CK treatments, and into the furrows for the M0C0, M0C, MC0 and MC treatments), when the ridge and furrow system built in July 2005 and in April 2006, 2007 and 2008. After harvest of every year, the configuration of double ridges and furrows, as well as the plastic film in the M0C0, M0C, MC0 and MC treatments were left in the field until the new system of ridge-furrow and plastic mulching was rebuilt the following year, and subgrooves with plastic film were used for four years. The crops were millet, field pea, spring wheat and potato, grown in this order from 2005 to 2008. The planting date, seeding rate, depth of seeding and harvesting date of each crop is presented in Table 1. Millet, field pea and spring wheat were planted with a special planting machine, and potato was planted with a spade.

2.3. Sampling and measurements

During the growing seasons, the soil temperature at the 5 cm depth between the plant rows was recorded at 08:00, 14:00 and 20:00 h with a geothermometer (Zhou et al., 2009; Wang et al., 2011; Li et al., 2013), every day for three consecutive days in the middle of every month. The mean daily soil temperature was calculated as the average of the three daily readings.

Soil moisture was measured gravimetrically (g g^{-1}) to a depth of 100 cm at 20 cm intervals (0–40 cm in M0C and MC) in the middle of every month of each growing season, using a soil auger (4 cm diameter, 20 cm height), and soil water content was measured in the furrows of the M0C0, M0C, MC0 and MC treatments. The soil samples were collected into self-sealing plastic bags in the field, and upon arrival at the laboratory each sample was immediately enclosed in an aluminum soil box. All soil samples were weighed within 1 h after collection to obtain the fresh weights, and oven-dried at 105 °C to a constant weight, then weighed again to determine the gravimetric water content. The soil bulk density at 0–100 cm depth was determined using the core method. The bulk of stainless ring was 100 cm^3. Nine core samples were collected randomly from the experiment field in July before the beginning of the experiment in 2005, the core samples were immediately weighed, then dried at 105 °C for 24 h to a constant weight and reweighed. The average bulk density was 1.15 g cm^{-3} in the soil to a depth of 20 cm, and 1.22 g cm^{-3} in the 20–100 cm layer. The moisture content volumetrically was calculated by soil gravimetrical moisture multiplied by soil bulk density.

Millet, field pea and spring wheat were harvested by hand, and potato was harvested by spade. The crop yields were estimated based on the total plot land area, including the ridges and furrows. In order to prevent the change and consumption of the chemical composition of the plants, all samples of herbage, grain and tubers

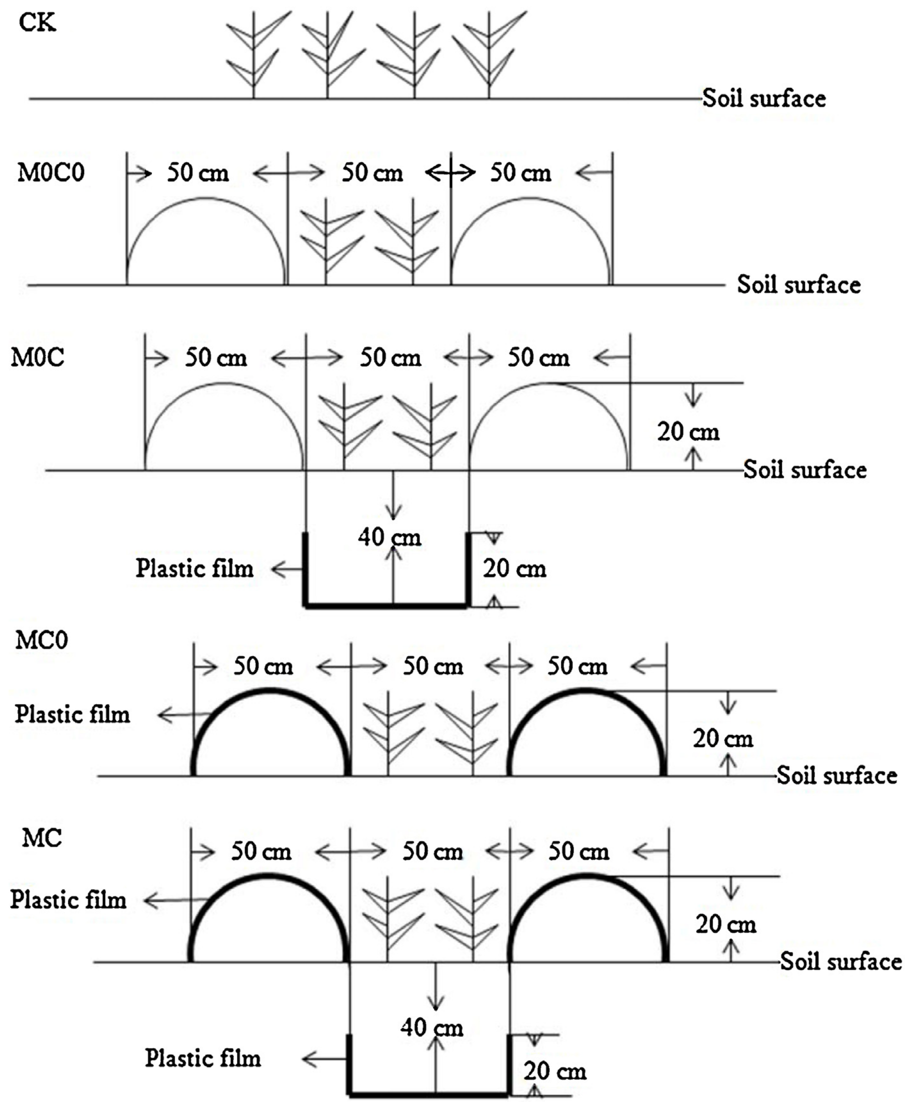

Fig. 1. Planting methods in the different treatments. CK: flat plot with no mulching; M0C0: alternating ridges and furrows with no mulching; M0C: alternating ridges and furrows with no mulching, subgrooves mulched with plastic film; MC0: alternating ridges and furrows, only the ridges mulched with plastic film; MC: alternating ridges and furrows and subgrooves, the ridges and subgrooves mulched with plastic film.

were oven-dried at 105 °C for 1 h, then at 70 °C for a minimum of 72 h. In this study, crop yield refers to the grain yield of spring wheat and field pea, tuber yield of potato, and aboveground biomass of millet.

2.4. Statistical analysis

Statistical analysis was carried out using the SAS software package (SAS Institute, 1990). The differences among treatments were evaluated with the least significant difference (LSD) at $P < 0.05$. Multiple comparison tests were used to determine whether differences existed in the crop yields at $P < 0.05$.

3. Results

3.1. Precipitation and growing periods of crops

Most precipitation occurred between 2006 and 2008 were dry years, with respective precipitations of 195 and 254 mm (Fig. 2); 2005 was an average year, with 316 mm of precipitation; and 2007 was a wet year, with 390 mm of precipitation (Fig. 2). Potato

Table 1
Planting dates, seeding rates, depths of seeding and harvesting dates for crops grown in the experiment

Crop	Planting date	Seeding rate ($kg\,ha^{-1}$)	Depth of seeding (cm)	Harvesting date
Millet	Early July	15	3	Late October
Pea	Early April	135	4	Late July
Spring wheat	Early April	180	3	Early August
Potato	Late April	1500 (fresh tuber)	10	Late September

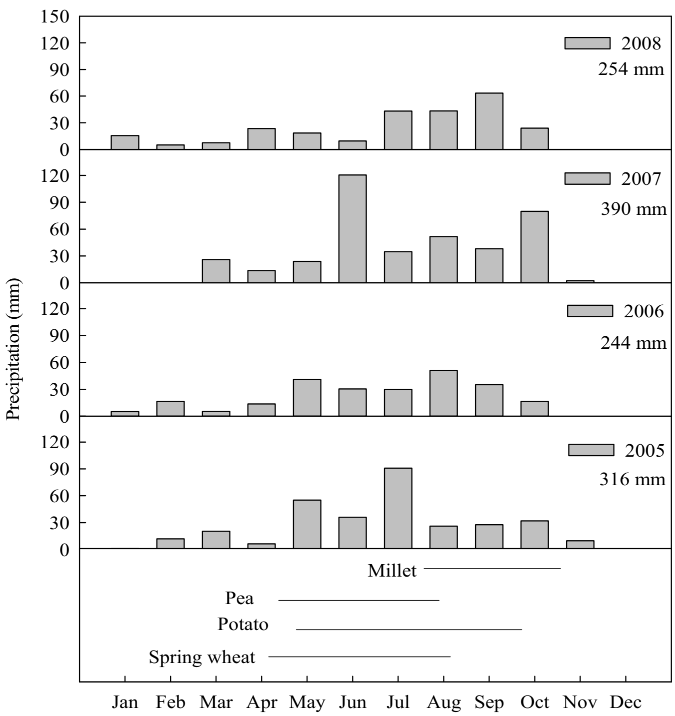

Fig. 2. Distribution of precipitation (bar graphs) at the study site over the period of the 4-year experiment (2005–2008) and growth periods of each crop (millet, field pea, potato and spring wheat).

had the longest growing period of 156 days, followed by millet, field pea and wheat (100–120 days). Precipitation during potato growth accounted for approximately 80% of total annual precipitation, but for millet, field pea and wheat it accounted for about 50%.

3.2. Dynamics of soil temperature

In 2005, the soil temperature at the 5 cm depth did not differ significantly among the treatments in July (Fig. 3). In August, the soil temperature was significantly higher in the M0C and MC treatments than in the CK, and no significant differences were observed in the M0C0, MC0, M0C and MC treatments. In September, the soil temperature was significantly higher in the MC0, M0C and MC than in the M0C0. In October, the soil temperature was significantly higher in the M0C than in the CK, with no significant differences observed in the M0C0, MC0, M0C or MC. The high in temperature in the treatments with subgrooves than in the treatments with no subgrooves in August and September only occurred at 14:00 and 20:00 h of the day (Fig. 4).

In 2006, the soil temperature was significantly higher in the M0C and MC than in the CK in April (Fig. 3). In May the soil temperature was significantly higher in the M0C and MC than in the CK, M0C0 and MC0, and the soil temperature in the late growing season was higher in the M0C than in the other treatments.

In 2007, the soil temperature did not differ significantly among treatments in May and July (Fig. 3). In April and June, the soil temperature was significantly higher in the MC than in the CK and M0C0, and no significant differences were observed in the MC0, M0C and MC. In August, the soil temperature was significantly higher in MC than in other treatments. In September, the soil temperature was significantly higher in MC than in CK, M0C0 and

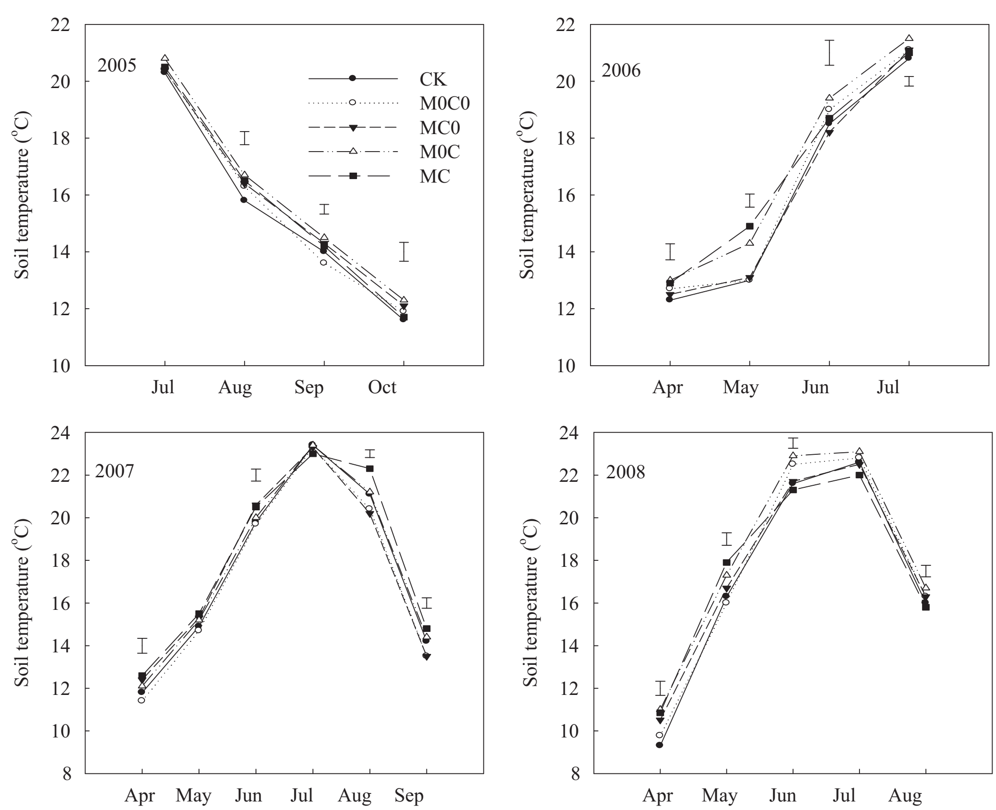

Fig. 3. Mean daily soil surface temperature at the 5 cm depth in the middle of the planting zones in different treatments during the 4-year experiment. Error bars are the LSD at $P \leq 0.05$.

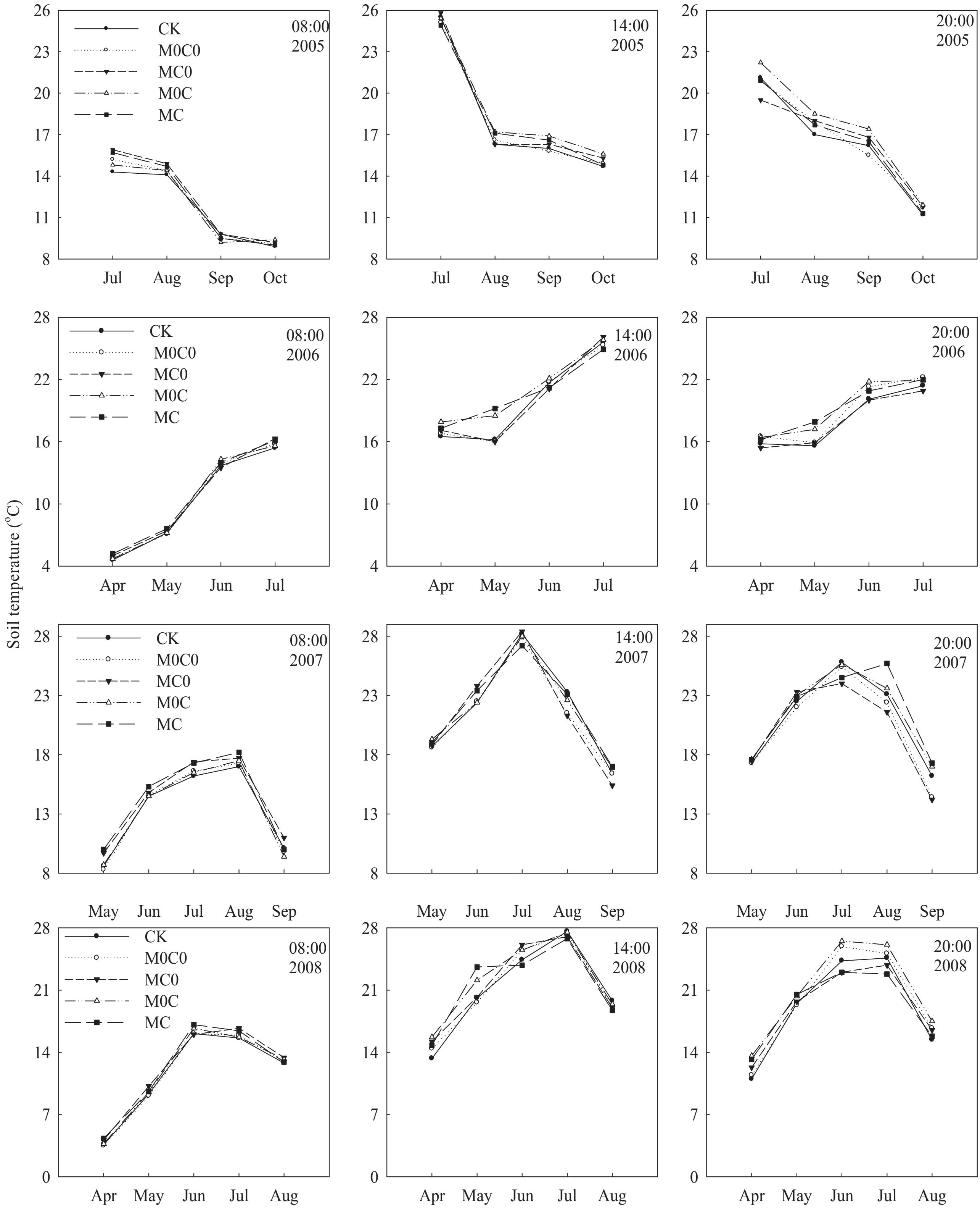

Fig. 4. Soil surface temperature at 08:00, 14:00 and 20:00 h of day at the 5 cm depth in the middle of the planting zones in different treatments during the 4-year experiment.

MC0, and no significant differences were observed in the M0C and MC.

In 2008, the soil temperature was significantly higher in the M0C and MC than in the CK and M0C0 in April and May (Fig. 3), and the high in temperature in the M0C and MC than in the CK and M0C0 only occurred at 14:00 and 20:00 h of the day (Fig. 4).

The average soil temperature of the 4-growing seasons was 16.7, 16.8, 16.9, 17.4 and 17.2 °C for the CK, M0C0, MC0, M0C and MC,

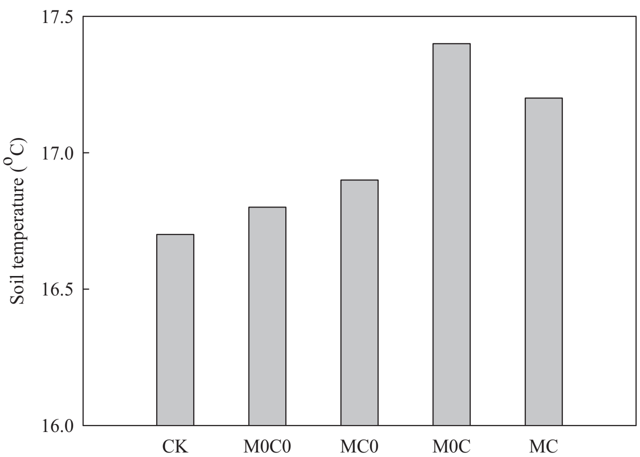

Fig. 5. Mean daily soil temperature of the 4-growing seasons at the 5 cm depth in the middle of the planting zones in different treatments.

respectively, and it is higher in the M0C and MC than in the CK, M0C0 and MC0 by 0.3–0.7 °C (Fig. 5).

3.3. Soil moisture and grain yield

2005 was an average year of precipitation, and the patterns of soil water content in the 0–20 and 20–40 cm soil layers were similar throughout the entire growing season (Fig. 6). The soil water content from August to October was always higher in the MC than in the CK and M0C0, and significant differences were observed in October. The average soil water content in the 0–20 cm soil layer from August to October was higher in the MC than in the CK and M0C0 by 5.6% and 5.9%, respectively, and it was higher in the MC than in the CK and M0C0 by 9.8% and 17.2%, respectively, in the 20–40 cm soil layer. In the 40–100 and 0–100 cm soil layers, the soil water content was always higher in the MC0 than in the CK and M0C0 throughout the entire growing season, and significant differences were observed in August and September.

2006 was a dry year, during which the soil water content was significantly higher in the MC0 than in the M0C0, M0C and MC in the 0–20 cm soil layer in April and May and the soil water content was higher in treatments with subgrooves than in those with no subgrooves in July (Fig. 7). The average soil water content in the 0–20 cm soil layer throughout the entire growing season was lower in the MC than in the CK, M0C0 and MC0 by 9.6%, 1.6% and 28.7%, respectively. The soil water content was significantly lower in the MC0 and MC than in the other treatments in the 20–40 cm soil layer during the entire growing season. The average soil water content in the 20–40 cm soil layer throughout the entire growing season was lower in the MC than in the CK and M0C0 by 29.1% and 31.4%, respectively. The patterns of soil water content in the 40–100 and 0–100 cm soil layers were similar throughout the entire growing season, and the soil water content was significantly higher in the CK and M0C0 than in the MC0 from April to June, while it was higher in the MC0 than in the CK and M0C0 in July.

2007 was a wet year, during which the soil water content was lower in treatments with subgrooves than those with no subgrooves in the 0–20 cm soil layer, and the soil water content was always higher in the MC0 and MC than in the other treatments from July to September (Fig. 8). The average soil water content in the 0–20 cm soil layer throughout the entire growing season was higher in the MC than in the CK by 10.8%. The soil water content was always higher in the MC0 and MC than in the other treatments in the 20–40 cm soil layer from May to September. The average soil water content in the 20–40 cm soil layer throughout the entire growing season was higher in the MC than in the CK and M0C0 by 20.6% and 18.9%, respectively. The soil water content was significantly higher in the MC0 than in the CK and M0C0 in the 40–100 and 0–100 cm soil layers during the entire growing season.

The change of soil water content between the CK and MC mainly occurred in the 20–40 cm soil layer during the growing seasons. In the 20–40 cm soil layer, compared to CK, the soil water content

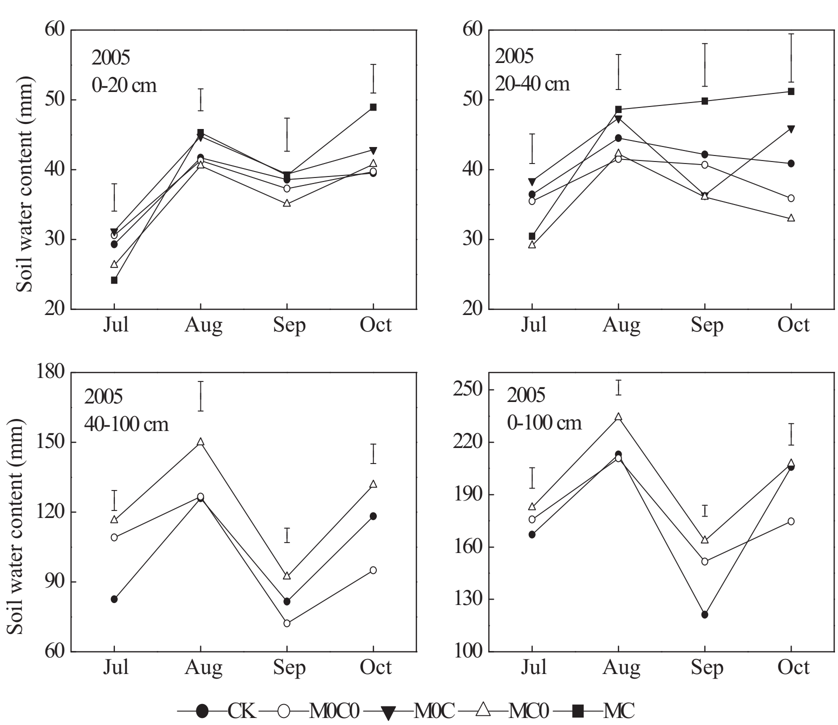

Fig. 6. Profile of the soil water content (mm) from the 0–20, 20–40, 40–100 and 0–100 cm layers in various treatments in 2005. Error bars are the LSD at $P \leq 0.05$.

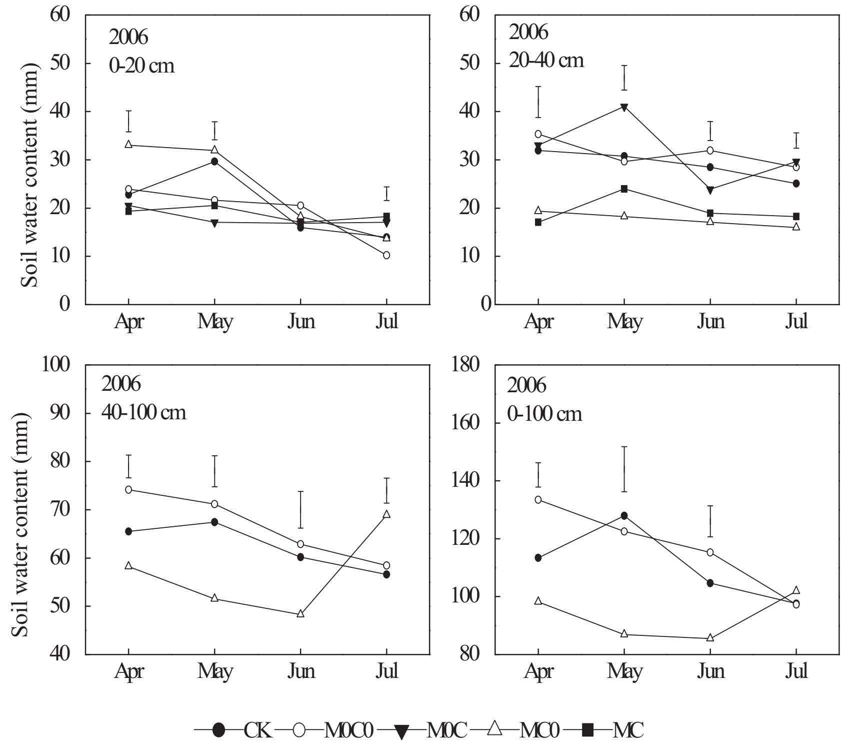

Fig. 7. Profile of the soil water content (mm) from 0–20, 20–40, 40–100 and 0–100 cm layers in various treatments in 2006. Error bars are the LSD at $P \leq 0.05$.

increased by 6.2–37.7% in average and wet years for MC, but that decreased by 28.4–50.6% in a dry year of 2006 for MC.

In 2005 and 2006, the yields of millet and filed pea were significantly higher in the MC than in the other treatments, and it was evident that there were significant potato yield responses to the ridges and subgrooves with mulched plastic film, as well as the interactions between them (Table 2). In 2007, the yield of potato was significantly higher in the MC and MC0 than in the other treatments, and it was evident that there were significant potato yield responses to the ridges and subgrooves with mulched plastic film, as well as the interactions between them. The technique of subgrooves with mulched plastic film significantly improved the ratio of large and moderate tuber yield to total tuber yield compared to the treatments with no

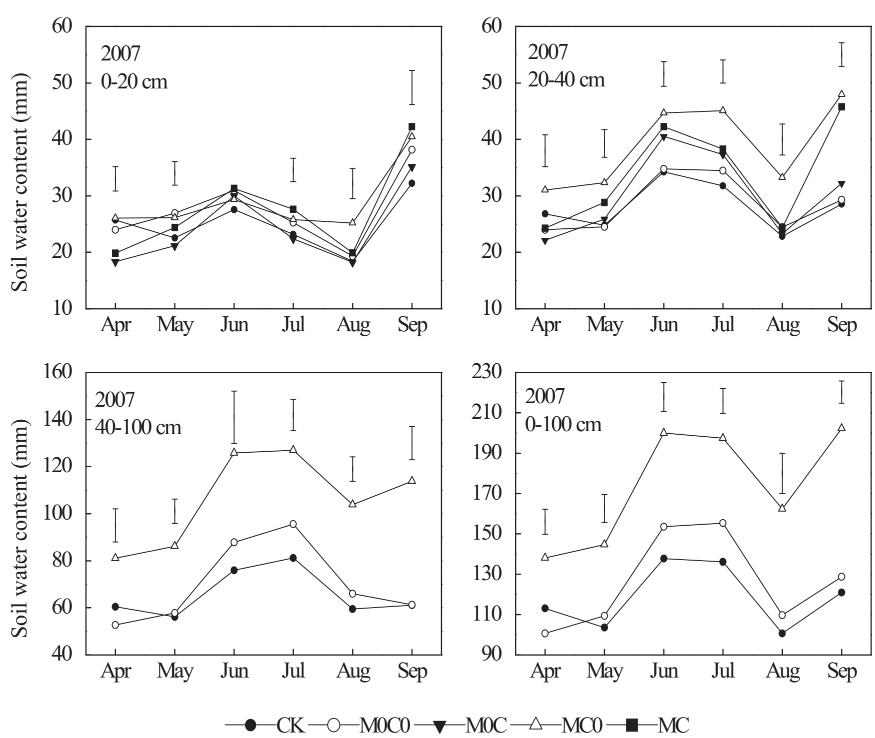

Fig. 8. Profile of the soil water content (mm) from the 0–20, 20–40, 40–100 and 0–100 cm layers in various treatments in 2007. Error bars are the LSD at $P \leq 0.05$.

Table 2
Crop yields (kg ha^{-1}) in various treatments during the 4-year experiment

Treatments	2005 Millet	2006 Pea	2007 Potato	2008 Wheat	Average over 4 years
CK	307c	416c	2423c	1196b	1086
M0C0	598b	817c	2978bc	1369b	1441
M0C	602b	1097bc	3842b	1497b	1760
MC0	642b	1572b	5449a	1774ab	2359
MC	1139a	2617a	5524a	2123a	2851
	F-value	F-value	F-value	F-value	
Subgroove mulched (SG)	28.24*	74.06*	19.41*	12.49*	
Ridge mulched (RM)	35.67*	194.6*	257.49*	48.96*	
SG*RM	8.16*	10.16*	14.92*	0.70	

CK: a flat plot with no mulching; M0C0: alternating ridges and furrows with no mulching; M0C: alternating ridges and furrows with no mulching, with the subgrooves mulched with plastic film; MC0: alternating ridges and furrows, with only the ridges mulched with plastic film; MC: alternating ridges, furrows and subgrooves, the ridges and subgrooves mulched with plastic film.
Values within a column followed by the same letter do not differ significantly at $P \le 0.05$. * Mean $P \le 0.05$.

subgrooves. The ratio of large and moderate-sized potato tuber yield to total tuber yield was higher in the treatments with subgrooves than in the treatments with no subgrooves by 21.7%. In 2008, the yield in MC was the highest of all treatments, and the yield was also significantly affected by the ridges and subgrooves with mulched plastic film. The average yield over the four years was higher in the MC than in the CK, M0C0, M0C and M0C by 163%, 98%, 62% and 21%, respectively (Table 2).

4. Discussion

In dryland areas at high altitude, low temperatures in the spring often result in poor establishment of crops (Liu et al., 2009; Zhou et al., 2009). Rapid seedling emergence is crucial for initial dry matter production and growth of crops in semiarid environments (Li et al., 2004; Zhou et al., 2009). In this study, we found that the soil temperatures in treatments with subgrooves were generally higher than those in treatments with no subgrooves during all four of the growing seasons, and higher temperatures in the spring promoted crop emergence in the MC, which was 3–10 days earlier than the other treatments. In this study, we found that the high in temperature in the treatments with subgrooves than in the treatments with no subgrooves during the growing seasons generally only occurred at 14:00 and 20:00 h of the day. It indicated that the increases of temperature in treatments with subgrooves are that the solar energy reflected by the plastic film at the walls and bottoms of the subgrooves heats up the soil inside the subgrooves.

Soil water content plays an important role in crop productivity, mainly in the semiarid areas of the world. The ridge and furrow rainfall harvesting system can improve the soil water content by collecting more rainwater from the top of covered ridges (Wang et al., 2011; Qin et al., 2014). Lin et al. (2006) reported that subgrooves were propitious to amending soil water condition in semiarid areas. In the present study, we found that ridges and subgrooves with plastic film mulching were propitious to maintaining topsoil water in average and wet years, while in dry years, subgrooves with plastic film mulching were conducive to maintaining soil water content. In dry years, the topsoil water content decreased due to severe drought and crop use, as the soil water in treatments with no subgrooves can move from the deep soil layer to the shallow layer, but the plastic film on the bottom of the subgroove blocked the water moving from the deep soil layer to the shallow layer, and led to lower soil water content in the treatments with subgrooves in comparison to the treatments with no subgrooves.

In this study, we found that there were significant grain yield responses to the ridges and subgrooves with mulched plastic film, as well as to the interactions between them. The increase of crop yields was possibly due to the increase of soil temperature and moisture under practices of the ridges and subgrooves with mulched plastic film. In 2006, the soil water content was significantly lower in the MC than in CK, M0C0 and M0C, and no significant differences were observed between the MC and MC0 during the entire growing season, but the field pea yield was significantly higher in the MC than the other treatments. In this region, crop yields are also affected by low supply of soil nutrients (Jiao et al., 2011; Liu et al., 2013a, 2013b; Yang et al., 2014), and it has been indicated that crop fertilizer use efficiency may be improved by blocking soil nutrients from leaching with the plastic film on the bottom of the subgrooves. We also found that using subgrooves with plastic film mulching significantly improved the ratios of large and moderate tuber yield to total tuber yield, compared with the treatments with no subgrooves (Fig. 9). In addition, seed germination and seedling establishment are key processes in plant development and yield formation during later periods of crop growth (Liu et al., 2009). In the present study, the emergence of potato in the M0C and MC was earlier than in the CK and M0C0. Seedlings which are established early can effectively use soil nutrients, thus promoting tuber growth and improving the ratio of large tuber yield to total tuber yield (Zhao et al., 2012; Qin et al., 2014). Finally, the subgrooves limited the root growth of potato and improved the vegetative growth (Jia et al., 2008).

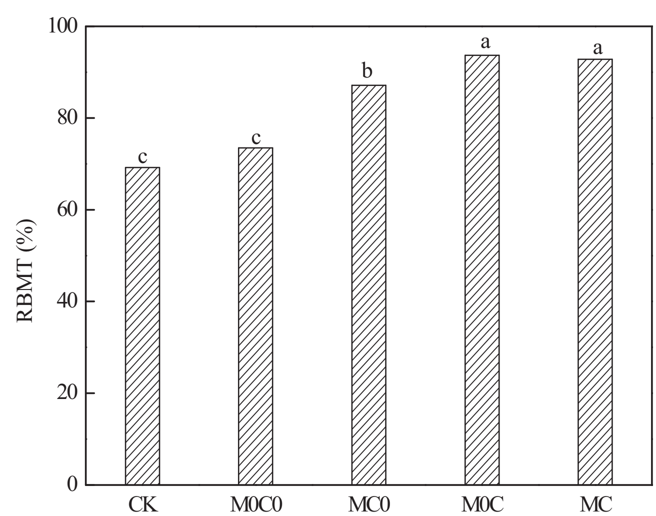

Fig. 9. Ratio of large and moderate-sized tuber yield to total tuber yield (RBMT) in various treatments in 2007. Different letters indicate significant differences at $P \le 0.05$.

5. Conclusion

The plastic film mulching with subgrooves improved topsoil temperature. In average and wet years, the ridges and subgrooves with plastic film mulching were shown to be propitious to maintaining topsoil water. The plastic film mulching with ridges and subgrooves improved the crop yields and the ratio of large and moderate potato tuber yield to total tuber yield. Therefore, the technique of using plastic film mulching with ridges and subgrooves is shown to be an effective practice for improving crop yields in semiarid agroecosystems, and should be widely applied in these areas.

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