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Full Length Research Paper

Effects of ridge and furrow rainfall harvesting system on *Elymus sibiricus* yield in Bashang agro-pastoral zone of China

He Feng[1,2], Wang Kun[1]*, Li Xiang Lin[2] and Liu Gui Xia[3]

[1]The College of Animal Science and Technology, China Agricultural University, Beijing, 100193, China.
[2]Institute of Animal Sciences, Chinese Academy of Agricultural Sciences (CAAS), Beijing 100193, China.
[3]Hebei University, Baoding, 071002, China.

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A ridge-furrow rainfall harvesting system (RFRHS) was designed to increase the available soil water for *Elymus sibiricus* artificial grassland in order to improve and stabilize its yield in the agro-pastoral zone of Bashang region in North China. Field experiments were conducted during the growth seasons in 2008 to 2010 to evaluate the effects of the RFRH system on soil temperature, soil water content and the yield of *E. sibiricus*. Specifically, the following three systems were investigated: ridge width 60 cm and furrow width 30 cm (MR60), ridge width 30 cm and furrow width 30 cm (MR30) and flat (CK). The results show that in regrowth periods, average daily minimum temperature of MR30 and MR60 in the furrow soil surface was 3.22 and 2.16°C, which were significantly higher than that of CK. Soil water content of MR60, was higher than that of MR30 and the latter was higher than that of CK in most of the experimental periods. Due to the improved hydrothermal condition, the three year average of annual yields of MR60 and MR30 was 3.14 and 2.77 t ha^{-1}, which was significantly higher and increased by 99 and 75% compared with CK, respectively.

Key words: *Elymus sibiricus*, ridge-furrow rainfall harvesting system (RFRHS), semi-arid area, perennial grassland, soil temperature, soil moisture.

INTRODUCTION

Bashang region was a typical agro-pastoral interlacing zone, in which the eco-environment was vulnerable and sensitive to environmental changes. However, it was an important water-source area and ecological barrier zone for Beijing, Capital city of China (Sheng et al., 2003). During the past century, some of the natural grasslands were reclaimed to cropland or vegetable land (Wang, 2000). Due to overused shallow underground water and frequent tillage, most of the soil became degraded, desertified and then abandoned (Zhao et al., 2005). In windy spring, dust was carried over by the strong wind to form sand storm, which accelerated erosion on soil degradation and also brought ecological risk to the economically developed area. Moreover, severe land degradation and population intensity resulted in a continuous decline for peasants' income, thus, exacerbated and perpetuated the problems of poverty (Zhao et al., 2005). One of the most effective methods used to solve this problem was to develop artificial grassland, since harvesting the vegetative part of forage had higher resistance to extreme weather condition as compared to harvesting the kernel part of other crops. Furthermore, perennial forage did not require continuous tillage in spring, so it could significantly hold down dust and keep water conservation.

Elymus sibiricus L., or Siberian wild rye, was widespread in diverse environment and had a wide adaptation (Dong and Zhang, 1980). It was one of the

*Corresponding author. E-mail: iashefeng@gmail.com. Tel: 86 10 62815997. Fax: 86 10 62815997.

Abbreviations: RFRHS, Ridge-furrow rainfall harvesting system; **MR60,** furrow width 30 cm; **MR30,** furrow width 30 cm; **CK,** flat.

Figure 1. Experimental area location. *****Beijing Capital of China. **•**Taipusi country, experimental area, solid line area, location of the Inner Mongolian.

most suitable species, which was well known by high resistance to diseases and tolerance to cold and drought, with high palatability and nutrition value (Dong and Zhang, 1980; Xiao, 1982; Li et al., 2005). However, extreme weather condition would cut short the usage life of forage, especially, extreme drought condition. In recent years, many studies showed that a ridge-furrow rainfall harvest system (RFRHS) could increase the efficiency of rainfall (Li et al., 2001; Li and Gong, 2002; Jia et al., 2006; Jin et al., 2010). RFRHS was the improved micro-catchment water harvesting (MCWH), which was particularly suitable to non-irrigated areas (Boers and Ben-Asher, 1982; Boers et al., 1986; Boers, 1994).

In order to increase the efficiency of the harvested water, the plastic film was used to cover the ridges (or runoff areas) based on the MCWH (Li et al., 1999). Rainfall, over 0.8 mm, could generate runoff on the plastic-covered ridge and was accumulated in the furrows (Li and Zhang, 2005). It was very useful in semi-arid condition, which had too much small and useless rainfall. Studies about corn, potato, spring wheat and alfalfa had shown that there was a considerable increase in yield (Li et al., 1999, 2001, 2007; Tian et al., 2003). Furthermore, RFRHS could increase soil surface temperature and prolong the growth period (Zhou et al., 2009). However, there were few experiences about RFRHS in Bashang region, as such, a more comprehensive analysis for the rules of soil temperature changes coupled with the transformation of soil water and heat should be further studied for *E. sibiricus*.

MATERIALS AND METHODS

Study site

The study was conducted between June 2008 and September 2010 at the Grassland Research Station of Chinese Academy of Agricultural Sciences (41°35′N, 114°51′E, 1400 m above sea level) in the Taipusi country, Inner Mongolian, China (Figure 1). It was located in the transitional zone between North China Plain and Inner Mongolian plateau. The climate was continental temperate monsoon, with cold winter, windy spring and warm and relatively rain-rich summer followed by short autumn. Mean annual

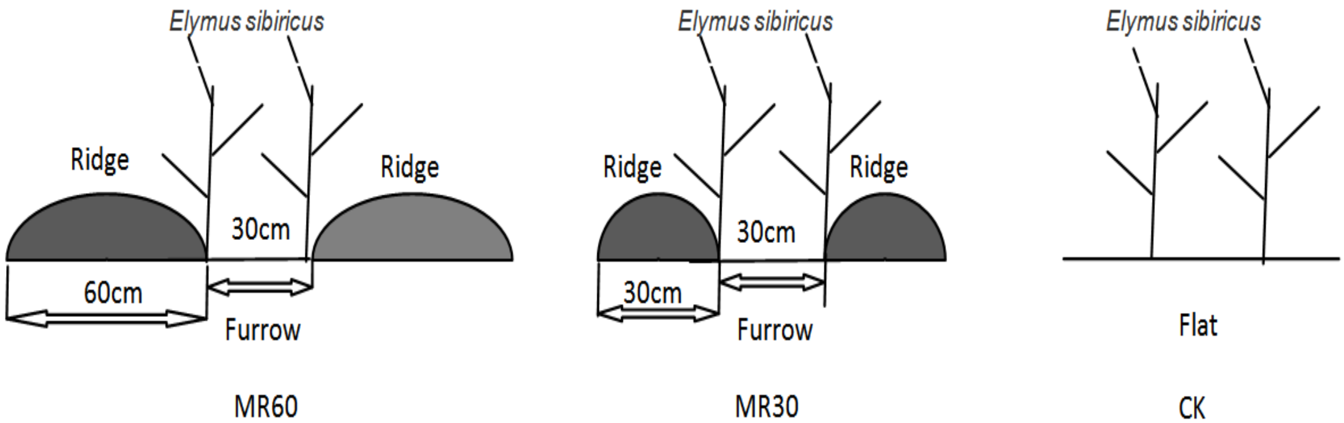

Figure 2. The schematic diagram presenting the three different systems in the study.

temperature of the site was 2.1°C and the coldest and warmest monthly mean temperature was -17.6°C in January and 17.8°C in July, respectively. Mean annual precipitation was 407 mm, which happened mainly (over 60%) in June, July and August. The zonal soil was sandy loam of loess origin, with a bulk density of 1.21 g cm^{-3} in the depth of 30 cm. The organic matter of the top soil (0 to 30 cm) prior to experiment was 14.4 gkg^{-1}.

Experimental design

This study included three different systems as shown in Figure 2: ridge width was 60 cm and height was 15 cm with furrow 30 cm (MR60); ridge width was 30 cm and height was 15 cm with furrow 30 cm (MR30). Each plot of both MR60 and MR30 consisted of four ridges and three furrows; flat plot as control system (CK), which was the traditional cultivated method. The experiment was a completely randomized block design with three replicates for each system. Every plot with a fixed length of 5 m, but varies widths according to the ridge widths. Plot area of MR60 was 3.3 × 5 m = 16.5 m^2, MR30 was 2.1 × 5 m = 10.5 m^2, plot area of CK was the same to MR30's. Before planting, the ridges were banked up with soil in the spot and covered with plastic film and furrows were leveled. The amount of 75 $kgha^{-1}$ urea (containing 46% N) was fertilized in the furrows. *E. sibiricus* seeds were sown by hand in broadcast sowing method at the rate of 2.25 g m^{-2} on 9 June, 2008.

Measurements

Soil temperature was measured with a MicroLite temperature plug and record mini data loggers (Fourtec Ltd., USA) in all plots at 15 min interval in a depth of 8 cm of the middle furrows during regrowth period from 21 April to 13 May and growth period from 6 August to 21 August in 2010. Hourly temperature (HT) was the mean of four times measuring data in an hour. Day maximum temperature (DMaxT) was the maximum value of HT in the day and day minimum temperature (DMinT) was the minimum value of HT in the day, and day average temperature (DAT) was the average value of 24 HT in the day.

Soil moisture was measured by using drying and weighing method in all plots, at 15 to 30 days intervals, in a depth of 30 cm of the middle furrow in 2008 and 2009. In 2010, soil moisture was measured with a frequency domain reflectometry (FDR) device PR2 Profile Probe (Delta-T Devices Ltd. UK) in all plots, at 15 to 30 days intervals, in a depth of 30 cm. Three probe tubes were installed at the middle furrow of each plot. Volumetric water content (VWC) was utilized to compare the difference among the systems in this study. The relationship between gravimetric water content (GWC) and VWC was: VWC = GWC × bulk density. *E. sibiricus* was first harvested at the boot stage (at the end of June or beginning of July) and then cut at the end of growth period (at the end of August or beginning of September), stubble was 5 cm height. For every harvest, the amount of 500 g fresh *E. sibiricus* in each plot was sampled and oven-dried at 105°C for 1 h and then at 85°C for 48 h to measure dry matter content. The yield was estimated based on the furrows, as well as the total plot area including the ridges and furrows.

Statistical analysis

All statistical analyses were performed using the SPSS 17.0 for windows (SPSS inc., Chicago, IL, USA). Differences of soil volumetric water content and *E. sibiricus* yield among systems were estimated by one-way analysis of variance (ANOVA) using Duncan's multiple range test method (P = 0.05). Differences of soil temperature among systems were estimated by paired-samples T Test. System effects were considered significant at $P<0.05$ level.

RESULTS

Weather conditions during the experimental period

During the three years of the experiment, the total precipitation was 445 mm in 2008, 256 mm in 2009 and 492 mm in 2010, respectively. The year of 2008 and 2010 were wet year, compared to the 20-year's average (407 mm). 2009 was an extreme drought year and the rainfall was only 62.9% of the 20-year average. Precipitation in 2010 was erratic and extremely abnormal and the rainfall was only 159 mm which was 32% of annual total precipitation from June to August when the plant showed vigorous growth, while in this region, the rainfall is usually 60 to 80% of the annual total precipitation during this period. The serious drought happened in June, since there was only 12.7 mm precipitation (Figure 3). The annual average temperature was 2.62°C in 2008, 2.90°C in 2009 and 2.1°C in 2010. All the three years were hot

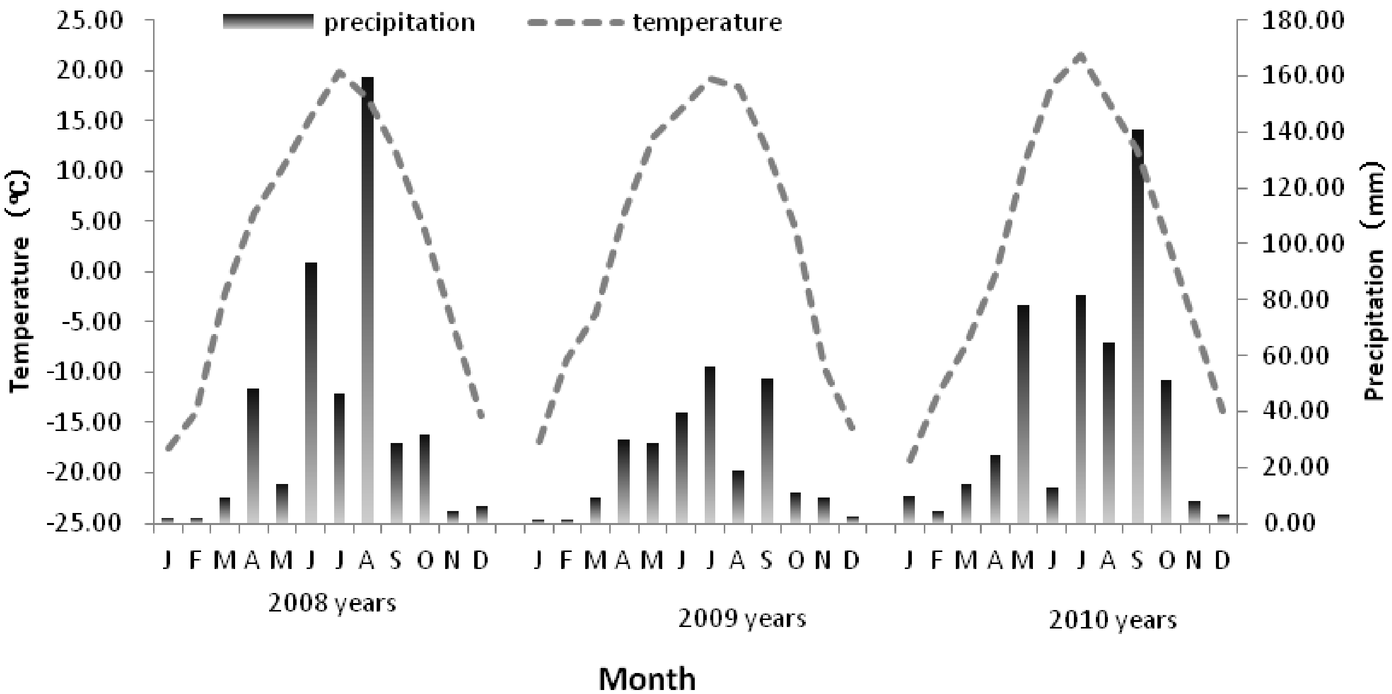

Figure 3. Changes of monthly air temperatures and precipitations in experiment site from 2008 to 2010. Data collected from the national meteorological station in Taipusi country.

years compared to the 20-year average (1.6°C). In the regrowth period, the monthly average temperature of April and May was 5.90 and 10.33°C in 2008, 5.92 and 13.42°C in 2009, and -0.32 and 10.82°C in 2010, respectively. The starting date of spring regrowth in 2010 was obviously behind schedule than that in 2009. In practical agricultural situation, the farmers reaped nothing from the rain fed fields both in 2009 and 2010.

Soil surface temperature

Micro-topography changing elicited the soil surface hydrothermal distribution. In regrowth periods and growth periods, traits of the soil temperature of ridge and furrow systems (MR60 and MR30) showed significant difference from CK. In regrowth period, DAT of MR30 was increased by 1.22°C, which was significant higher ($P<0.05$) than that of CK, whereas soil temperature of MR60 was not significantly different from CK. DMaxT of MR30 and CK was 1.49 and 1.58°C, respectively, which were higher ($P<0.05$) than that of MR60. DMinT of MR30 and MR60 was 2.08 and 1.02°C, respectively, which were higher ($P<0.05$) than that of CK (Table 1). The solar energy passed through the plastic-film and heated up the air and the surface soil of ridge and then the heat was trapped by the greenhouse effect (Zhou et al., 2009). Meanwhile, the ridge kept out part of solar energy of the furrow. Consequently, MR30 system had the highest soil DAT and DMinT and CK system had the highest soil DMaxT during the regrowth period (Table 1). Since the specific heat capacity of water was higher than that of soil, the lowest soil DAT and DMaxT happened in MR60, which accumulated more rainfall and had higher water content in the furrows.

During the regrowth period, HT from 10 p.m to 10 a.m of MR30 was higher than that of MR60 and CK, however, HT in CK was higher from 12 a.m to 5 p.m. In the extreme weather condition, HT in CK was lower than that in MR60 and MR30, furthermore HT in CK was below 0°C, which could hurt the regrowth seedling and HT in MR60 and MR30 was higher than 0°C. In growth period, DAT in MR30 and MR60 was 1.19 and 0.58°C, respectively, which were higher ($P<0.05$) than that in CK. DMaxT of MR30 was 1.17°C, which was higher ($P<0.05$) than that in MR60, whereas DMaxT of MR60 was not significantly different from CK. DMinT of MR30 and MR60 was higher ($P<0.05$) than that of CK by 3.15 and 2.87°C, respectively. During the growth period, HT of MR30 and MR60 was higher than that of CK from 10 p.m to 10 a.m. However, it had higher HT in CK from 12 a.m to 6 p.m. In rainy or cloudy day, HT of CK was lower than that of MR60 and MR30 all day long.

Soil moisture in furrows

Due to the fact that the transpiration coefficient of

Table 1. The specific soil temperatures at 8 cm depth of furrow (MR60 and MR30) and flat (CK) in regrowth period and growth period.

Treatment	Regrowth period			Growth period		
	DAT	DMaxT	DMinT	DAT	DMaxT	DMinT
MR60	5.60[b]	10.46[b]	2.16[b]	19.48[b]	23.2[b]	16.39[b]
MR30	6.90[a]	11.95[a]	3.22[a]	20.09[a]	24.37[a]	16.67[a]
CK	5.68[b]	12.04[a]	1.14[c]	18.90[c]	24.24[a,b]	13.52[c]

Values (mean) within the same column by the different letters were significantly different at 5% level. MR60 presented the system of 60 cm ridge with 30 cm furrow, MR30 presented the system of 30 cm ridge with 30 cm furrow and CK presented the system without ridge and furrow. DAT, Day average temperature; DMaxT, day maximum temperature; DMinT, day minimum temperature.

E. sibiricus was 498 (Liu and Chen, 2004) and the potential productivity was more than 15 t ha^{-1} (Li et al., 2005), *E. sibiricus* water demand was 747 mm to realize the potential productivity in this region.

The rainfall was around 300 mm during May to September (Figure 2) and the average runoff efficiency in this experiment (expressed as a ratio of runoff to rainfall) was 90% (Li et al., 2010), so we arranged the ratio of ridge to furrow as 1:1 (MR30) and 2:1 (MR60), which could increase the water supply to 570 and 840 mm, respectively. Since, the furrows with covered ridge could accumulate more rainfall than flat, soil moisture of MR60 and MR30 was higher than that of CK during most of the growing period. Figure 2 shows the soil volumetric water contents of the three systems measured monthly from 2008 to 2010. In July and September, 2008, soil moisture in the depth of 0 to 30 cm increased significantly with increase of the ridge width. In July and September, 2008, soil volumetric water content (SVWC) of MR60 was 24.72 and 22.33%, respectively, which were higher ($P<0.05$) than that of MR30 and the latter were higher than that of CK in the two months.

However, there was no significant difference in SVWC among the three systems in August (Figure 4A), which could be due to field water capacity and the extra rainfall would result in runoff out of the furrows, on the other hand, *E. sibiricus* in the furrow systems could be planted closer and consume more water than in CK. The year of 2009 was an extreme drought year (Figure 4B), SVWC of MR60 was 12.03 and 16.05% in July and August, respectively, which were higher ($P<0.05$) than that of MR30 and the latter were higher than that of CK. SVWC of MR60 and MR30 were higher than CK by28 and 17% in May, respectively. There was no difference in SVWC among the three systems in June. The year of 2010 was a year with rich rainfall. There was no difference in SVWC among the three systems in June and the beginning of July.

However, for the middle of July, beginning of August and the middle of August, SVWC of MR60 was 21.06, 23.74 and 17.74%, which were higher ($P<0.05$) than that of CK by increasing 31, 33 and 20%, respectively (Figure 4C).

E. sibiricus yield

The effects of the ridge-furrow system on *E. sibiricus* were significant. Field observation showed that *E. sibiricus* plants in the ridge-furrow system grow more rapidly and robustly than that in CK. The ridge-furrow system could increase the DMinT significantly and reduce the influences of cold weather; meanwhile, the furrows and planting belts could accumulate much more rainfall than the flat system. In 2009 and 2010, the starting date of spring regrowth for MR60 and MR30 was seven to 12 days earlier than that for CK. *E. sibiricus* growing in the furrows (MR60 and MR30) were taller, stronger and with larger leaves as compared with those growing in CK. Table 2 shows the *E. sibiricus* yields obtained from the fields at the experimental site from 2008 to 2010. The yields were calculated based on the furrow area (FA), as well as on the plot area (PA), which included both areas for ridges and furrows. In 2008, the yields in MR60 and MR30 were significantly higher than that in CK per FA, however based on PA, the yield in CK was higher than that in MR60 and MR30 (Table 2).

The yield in MR60, either per FA or per PA, was significantly higher than that in MR30 and the latter was higher than that in CK both in 2009 and 2010. The ridge-furrow ratio affected the total yield significantly. Higher ridge-furrow ratio could accumulate more rainfall in the furrows. However, as a trade-off, the area of planting belt would be reduced. Lower ridge-furrow ratio could increase cultivated area, but could not accumulate enough rainfall.

The best ridge-furrow ratio should consider the runoff efficiency (Li and Zhang, 2005), average rainfall of experimental site and *E. sibiricus* water demand together. As shown in Table 2, in 2008, the yield base on FA of MR60 and MR30 increased with 2.00 and 0.6 t ha^{-1} as compared with CK, respectively. On the contrary, the yield based on PA of CK increased with 0.84 and 0.83 t ha^{-1} as compared with that of MR60 and MR30, respectively. In 2009, the yield based on FA of MR60 and MR30 increased with 14.40 and 8.14 t ha^{-1} as compared with CK, respectively, and the yield based on PA of MR60 and MR30 increased with 3.72 and 3.26 t ha^{-1} as

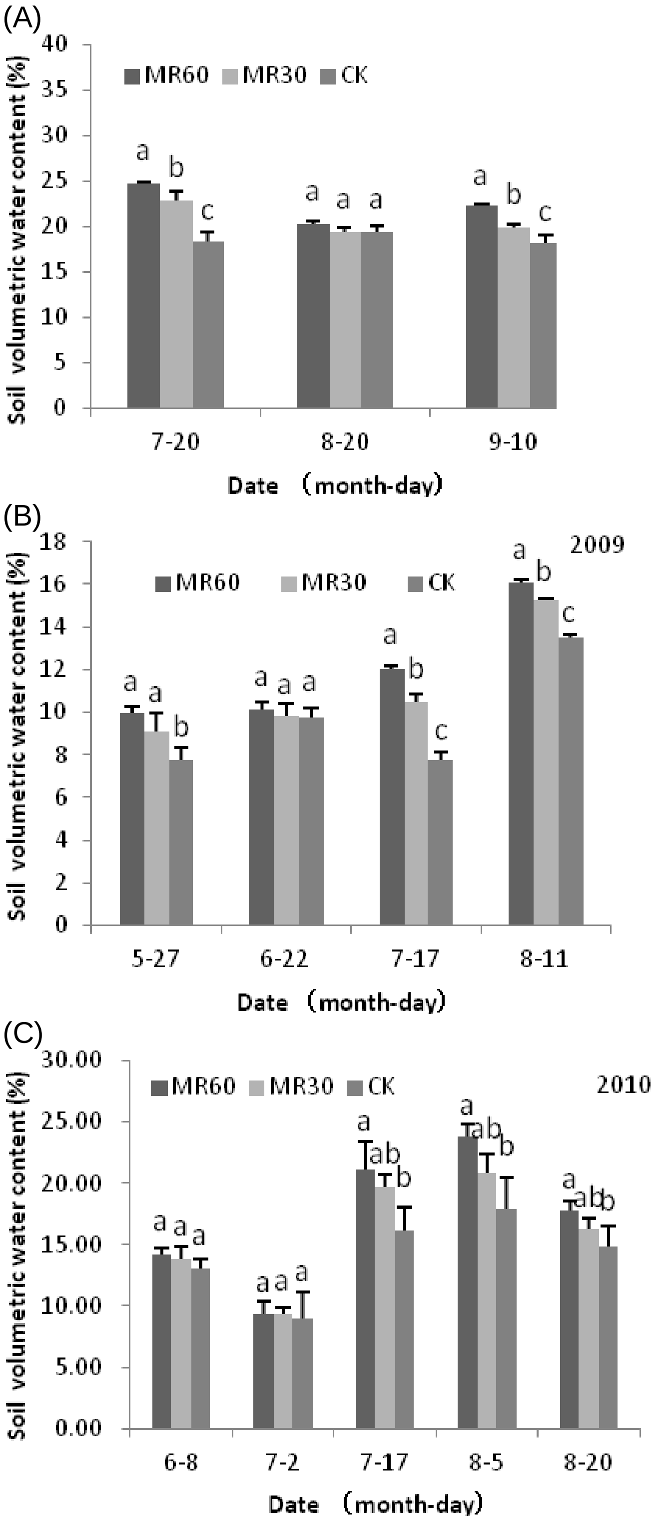

Figure 4. The comparison of soil volumetric water content (SVWC) at 30 cm depth for the three systems as MR60, MR30 and CK during the growth period from the year of 2008 (A), 2009 (B) and 2010 (C). In the legends: MR60, ridge width was 60 cm with 30 cm furrow; MR30, ridge width was 30 cm with 30 cm furrow, CK, flat. The means (columns) labeled with the different letters within each growing (date) were significantly different at 5% level (Duncan's multiple range test).

compared with CK, respectively. In 2010, the yield based on FA of MR60 and MR30 increased with 7.10 and 3.15 t ha^{-1} as compared with CK, respectively, and the yield based on PA of MR60 and MR30 increased with 1.80 and 1.15 t ha^{-1} as compared with CK, respectively.

Earlier studies showed that the highest yield of *E. sibiricus* usually occurred in the second and the third year (Dong and Zhang, 1980). In this study, the yield for conventional cultivation or CK in the second year was even lower than that in the first growing season, which could be due to the extreme drought weather condition in 2009. However, while drought did not affect the yield in ridge-furrow systems, the yield of MR60 was even similar to that of irrigation systems (Li et al., 2005). In 2010, the yield in ridge-furrow system was affected by the continuous drought in June and lower than that in 2009. The 3-year average of annual yield base on FA of MR60 and MR30 increased with 7.84 and 3.96 t ha^{-1}, respectively, as compared with CK.

The increase in yield based on FA reflected the accumulated water collection in the furrows, where the microenvironment would be beneficial for plant growth, but it did not reflect the normal agricultural situation where the yield would also depend on the total land area. From this point of view, even by considering the total land area, the advantages of MR60 and MR30 were also obvious. The average annual yield of the three-year period based on the PA of MR60 and MR30 increased with 1.57 and 1.19 t ha^{-1} or by 99 and 75% as compared with CK, respectively.

Conclusion

The systems of covered ridge and furrow can significantly enhance the accumulation of rain water, moisture of furrow soil and *E. sibiricus* productivity. In the system, the ridges were used as catchment for the accumulation of rainfall and the furrows were used as the planting areas with increased water content in soil, which could be due to the runoff from the ridges.

Meanwhile, the ridge-furrow system could also significantly enhance DMinT of furrow and reduce the cold weather damage to *E. sibiricus* during regrowth period. Furthermore, higher temperature could promote the plant growth during growth periods.

Due to the improved hydrothermal condition in covered ridges and furrows system, the productivity of *E. sibiricus* and the ability of withstanding extreme weather condition were significantly increased, and the latter was even more important for *E. sibiricus* cultivation. In the future, erratic rainfall and extreme coldness issues associated with global climate changes may become the serious problems, especially in the semi-arid areas. Covered ridge-furrow system could ensure the perennial grassland productivity of rainwater harvesting system. However, the economic efficiency of the system would need further study and investigation.

Table 2. *Elymus sibiricus* yield (t ha^{-1}) obtained from the three systems from 2008 to 2010.

Treatment	2008		2009		2010		3-year average	
	Per FA	Per PA	Per FA	Per PA	Per FA	Per PA	Per FA	Per PA
MR60	4.26[a]	1.42[b]	16.02[a]	5.34[a]	7.95[a]	2.65[a]	9.42[a]	3.14[a]
MR30	2.86[b]	1.43[b]	9.76[b]	4.88[b]	4.00[b]	2.00[b]	5.54[b]	2.77[a]
CK	2.26[c]	2.26[a]	1.62[c]	1.62[c]	0.85[c]	0.85[c]	1.58[c]	1.58[b]

Values (mean) within the column by the different letters were significantly different at 5% level (Duncan's multiple range test). MR60-ridge width is 60 cm with furrow 30 cm, MR30-ridge width is 30 cm with furrow 30 cm, CK-flat. FA, Furrow area; to which the yield data in this column is related it does not include the area occupied by the ridges. PA, Plot area to which the yield data in this column were related. It includes area occupied by both the ridges and furrows.

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