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ORIGINAL ARTICLE

Growing Characters of Proso millet (*Panicum miliaceum* L.) In Response to Different Rainwater Harvesting Practices in Semi-arid Region of the Loess Plateau in China

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In semi-arid and arid areas, crop growth is mainly limited by low rainfall (mm). Using plastic film-mulched and special soil tillage can be employed to harvest limited rainfall for crop growth so as to assure food production. The objective of this work was to find out how to exploit limited rainfall (mm) to increase yield of proso millet. Effects of different rainfall harvesting systems based on plastic film-mulched in proso millet were managed in semi-arid regions of Loess Plateau in 2010-2012, and soil type that study involved was calciccambisols. The hypothesis was that proso millet could improve growth and yield of proso millet by using rainfall harvesting system. Experiment designed three rainfall harvesting systems based on plastic mulched and no mulching (NM) as a control. A flat plot with no mulching was a control (NM), the width of furrow was 60 cm with 60 cm wide ridge (P60), the width of furrow was 60 cm with 100 cm wide M-shaped ridge (M160), and the width of furrow was 40 cm with 40 cm wide W-shaped ridge (W80). Control plot and systems were laid out in a randomized block design with three replications. Only the ridge was mulched with white plastic film. The results showed as follows: rainfall harvesting systems based on plastic film-mulched could increase water content of topsoil by 19.6%-43%, move up in temperature of topsoil by 0.1°C-2.7°C, improve agronomic traits ($P<0.05$), and increase yield by 96.8%-115.3% ($P<0.05$) and WUE by 120.2%-179.3% ($P<0.05$) compared with those of NM, respectively; "W-shaped" system performed advantage enough among all rainfall harvesting systems, increased water content of topsoil and temperature of topsoil, and separately increased yield and WUE of proso millet by 115.3% and 179.3% compared with those of NM ($P<0.05$) in three growing seasons; average rate of yield increase of proso millet in all rainfall harvesting systems tended to be quadratic function correlated with the rainfall (mm) ($R^2=1$); rainfall harvesting systems had better effect on improving plant heights at early growing stage of proso millet than those at later growing stage. The hypothesis was supported by these findings that suggested rainfall harvesting systems with plastic film-mulched could improve yield and water use efficiency of proso millet and have affection effectively at early growing stage of proso millet, increasing yield of rainfall harvesting system was limited by abundant rainfall (mm) and had to be suitable for 250 mm-300 mm rainfall of growing seasons for proso millet; "W-shaped" system performed well in semi-arid areas.

Keywords: rainfall saving technology; ridge-furrow tillage; rain-fed areas

Introduction

Proso millet (*Panicum miliaceum* L.) is an important food crop in semi-arid region of the Loess plateau (Zhang et al., 2012), still yield of proso millet remains low under rain-fed agriculture conditions because rainfall is not adequate to meet evaporation requirement during growing seasons (Jaetzold R et al., 2006; Xie et al., 2010; Li et al., 2013).

To increase yield of proso millet and ensure food supply in dry-land areas, rainfall harvesting technology for planting proso millet is necessary for practicing. Conservation agriculture is very helpful in maintaining soil moisture level through the use of cover crops and crop residue mulch retention (Derpsch, 2005; Hobbs, 2007), provides weed control and yield benefits (Murungu et al., 2010; Musunda, 2010; E. Dube et al., 2012), improves economic characters of crops (Zentner et al., 2002) and soil organic matter (Zentner et al., 2004), and increases yield (Lafond et al., 1996; Chen et al., 2011), respectively. Whereas this technique has uncertain yield (Mahli et al., 1988; Canarache and Dumitru, 2008; Xie et al., 2008) that depends on soil type (Tolk et al., 1999), climate (Lampurlanes et al., 2002), and land slope (Zhang et al., 2009). Besides, a mulching technique with mixed sand and gravel adopted in the northwestern regions has great effects on reducing evaporation and runoff, improving water infiltration, increasing soil temperature, maintaining soil water and fertility (Gale et al., 1993; Modaihsh et al., 1985; Van wesemael et al., 1996; Nachtergaele et al., 1998; Xie et al., 2010, 2006), but quite high construction cost renders sand-gravel mixture mulch technique to use on a commercial scale difficult (Wang et al., 2004b; Yajun et al., 2011). Mulching practices with plastic film is introduced in 1978 and has spread quickly and widely, especially in rain-fed regions because it makes limited rainfall utilized effectively (Dong et al., 2009), endures water lost under evaporation (Liakatas et al.,1986; Muller, 1991), redistributes moisture in the soil, alleviates water stress to some extent (Li et al., 2004), and keeps topsoil warmer and moist (Li et al., 2001, 1999; Song et al., 2002; Wang et al., 2003), respectively. Meanwhile, plastic film-mulched improved rate of photosynthesis (Li et al., 1999) and roots growth of crops

(Li et al., 2004b), therefore plastic film-mulched can increase crops yield (Ramakrishna et al., 2006; Luis Ibarra-Jimenez et al., 2011), water use efficiency (Tian et al., 2003; Zhou et al., 2009), and economic return (Chakraborty et al., 2008).

Currently, rainfall harvesting system is feasible alternatives for rain-fed agricultural production (Majed and Abdullah, 2011), and this system with furrows and plastic film-mulched ridges was effective farming practice that was used to solve problems of water shortages over many years in arid and semi-arid regions (Zhu et al.,1994; Zhao et al., 1995; Gao et al., 2008). Rainfall harvesting system with furrows and plastic film-mulched ridges was more effective on improving crop production (Lal et al., 1984; Wang et al., 2013). Li et al. (2001) reported that plastic mulched ridge and furrow rainfall harvesting (PRFRH) system improved water efficiency and increased maize yield over the bare ridge and furrow rainfall harvesting (RFRH) system under semiarid conditions in northwest China. Rainfall harvesting system with furrows and plastic film-mulched ridges can be an optimal practice to improve runoff efficiency, rainwater harvesting, crop yield, water use efficiency (WUE) (Li et al., 2000; Zhang et al., 2006; Wang et al., 2009), and produce greater economic benefit than conventional cultivation (Zhou et al., 2009; Liu et al., 2009; Shuhuai et al., 2012).

In recent years, despite the effects of rainfall harvesting systems on proso millet are yet be reported in semi-arid areas of north China (Qu et al., 2012), the objective of this study was to explore optimum rainfall harvesting systems in proso millet, including valid stage and limiting factor of rainfall harvesting system. The hypotheses of this study were that (a) rainfall harvesting systems could increase water content of topsoil and temperature of topsoil and improve proso millet growth, yield and WUE; (b) rainfall harvesting systems took effect at the early stage of proso millet; (c) rainfall harvesting system performed well depended on rainfall (mm).

Study area and data analysis

Study site description

Rainfall harvesting systems with furrows and plastic film-mulched ridges were conducted at Canghemao Experimental Station, Northwest A & F university, Fugu, Shaanxi province (39.09°N, 111.01°E and altitude 1000 m) during 2010-2012 seasons. The study site is dry-land regions with annual mean precipitation of 366.2 mm; a mean annual temperature is 9.1°C with a maximum of 38.9°C and a minimum of -24°C; an average annual pan evaporation of 1092.2 mm; an average annual sunshine duration of 2890 h and a frost-free period of over 177 frost-free days. Soil type is calciccambisols whose properties at each depth were showed in table 1. Analysis of the topsoil (0-20 cm) obtained the following results: an organic C content of 19.32 g kg^{-1}, a nitrate N content of 1.2 g kg^{-1}, an available P content of 6.4 mg kg^{-1}, an available K content of 89 mg kg^{-1}, an ammonium N（NH4^{+}+NO3^{-}）content of 44.3 mg kg^{-1} , and a soil bulk density of 1.50 g cm^{-3}.

Table 1. Properties of the different soil layers at the experimental site.

Soil layer depth (cm)	**Soil bulk density (g·cm^{-3})**	**Soil porosity**	**Wilting coefficient (g·kg^{-1})**	**Field capacity (g·kg^{-1})**
0-20	1.50	0.43	25	48
20-40	1.64	0.38	30	57
40-60	1.63	0.39	27	51
60-80	1.62	0.39	26	49
80-100	1.52	0.43	22	41

Experimental design

In this study, three rainfall harvesting systems were designed as follows: the width of furrow was 60 cm with 60 cm wide ridge (P60) (Figure 1), the width of furrow was 60 cm with 100 cm wide M-shaped ridge (M160) (Figure 2), and the width of furrow was 40 cm with 40 cm wide W-shaped ridge (W80) (Figure 3). A flat plot with no mulching (NM) is as a control. Plots of P60, M160 and W80 with areas of 4.8×5 m^2, 6.4×5 m^2 and 3.2×5 m^2 were composed of four ridges and furrows alternately. Plot of NM had an area of 3.2×5 m^2. All systems and control plot had three replications that were arranged in a randomized block design, and buffer row between treatments was 1 row. Ridges of P60, M160, and W80 were covered with 0.008 mm white plastic film (Height: 10 cm), and both ends of plastic film were perpendicular to furrow surface and embedded in soil (Depth: 5 cm). The entire experimental area was ploughed after all fertilizers (34.5 N kg ha^{-1}, 9.0 P2O5 kg ha^{-1}) were incorporated into the soil surface (Plough depth: 20 cm) according to conventional fertilizing method. The cultivar "Yumi 2" of proso millet with density of 5.0×105 plants ha^{-1} were sown on 11 June and harvested on 25 September in 2010, sown on 12 June and harvested on 23 September in 2011, and sown on 15 June and harvested on 27 September in 2012, respectively.

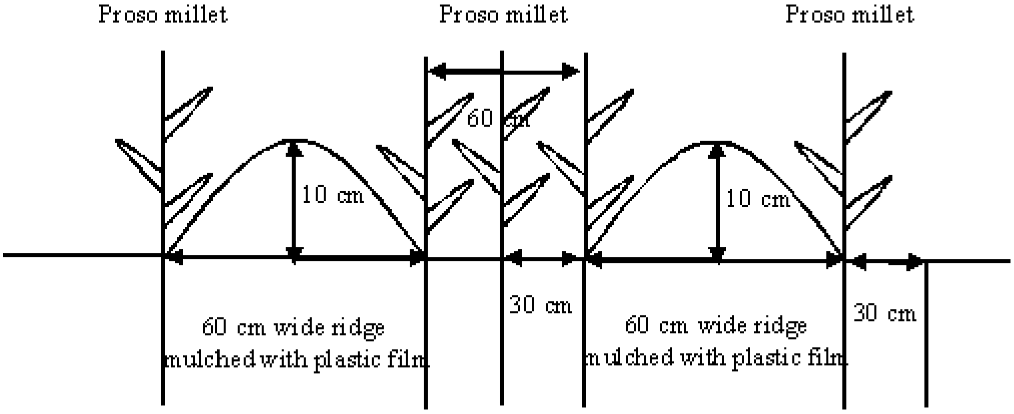

Figure 1. P60, the rainwater harvesting practice with 60 cm wide ridges mulched with plastic film.

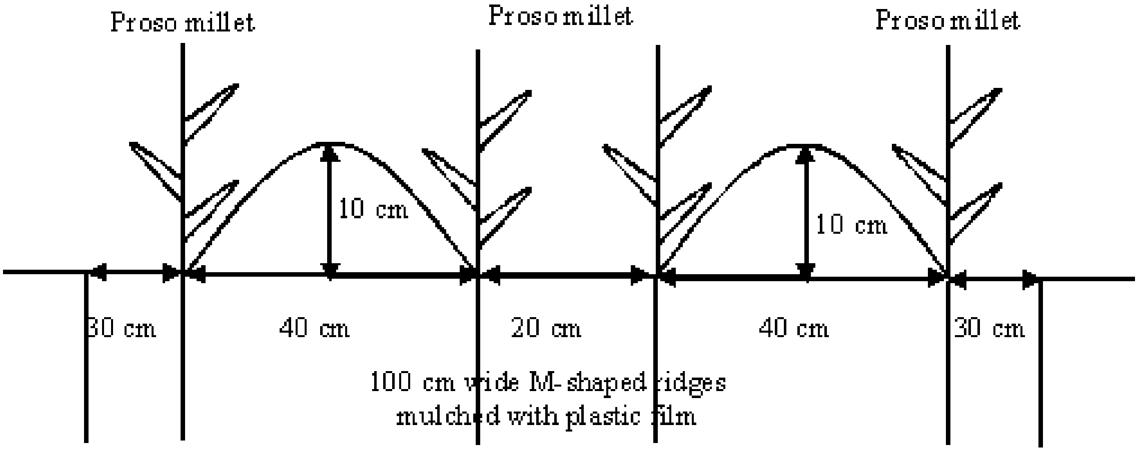

Figure 2. M160, the rainwater harvesting practice with 100 cm wide M-shaped ridges mulched with plastic film.

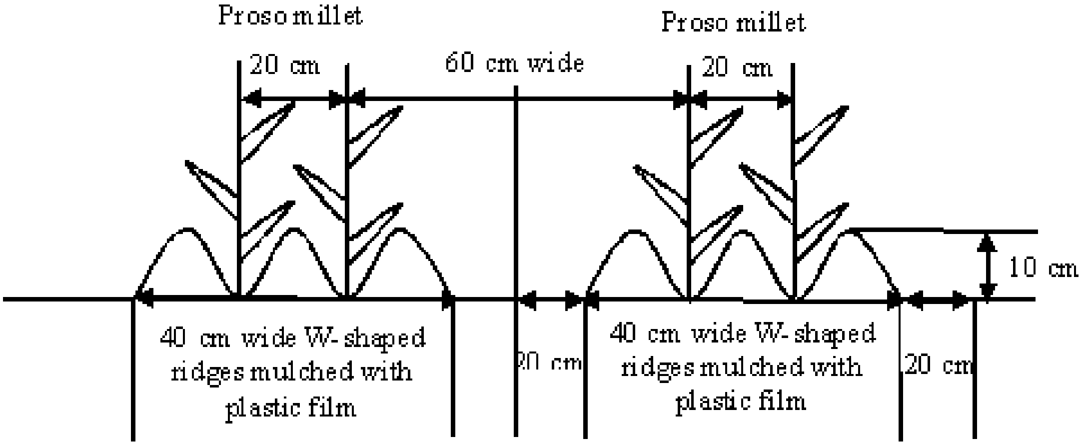

Figure 3. W80, the rainwater harvesting practice with 40 cm wide W-shaped ridges mulched with plastic film.

Sampling and measurements

Soil temperature at 10 cm soil layer was recorded in planting furrow of P60, M160, W80 and NM every two weeks until 60 days after sowing and the 10: 00 reading in the morning.

The water content in 0-100 cm soil profile was determined at depth intervals of 20 cm. Measurements were made approximately every two weeks during the growing seasons of proso millet. Soil water storage in the profile was considered to be the total storage (0-100 cm). Crop evapotranspiration (ET_c) was determined using the formula (Zhang et al., 2011):

$$ET_c=P+SW_p-SW_h+I-R-D$$

In which, P is the precipitation (mm) during the crop growth season; SWp is soil water storage (mm) at planting stage based on mean value of furrow and ridge; SWh is soil water storage (mm) at harvesting stage based on mean value of furrow and ridge; I is the amount of irrigation (mm), which was negligible due to no irrigation in this study site; R is surface runoff that was negligible due to barriers separating the plots that blocked runoff along furrows and ridges of rainfall harvesting systems; D is the amount of water lost due to deep drainage (mm) that was negligible due to 30 m deep water layer and less rainfall (Wang et al., 2004a).

Water use efficiency (WUE) of proso millet was calculated as grain yield (GY) in t ha^{-1} divided by total water use in mm (Evaluated as ET_c in the present study):

$$WUE=GY/ET_c$$

Data analysis

All data were analyzed by SAS V6 and Microsoft Excel 2003 software, and mean values were compared by Duncan' method ($P<0.05$).

Results

Soil water

The water content of topsoil with different systems is showed in table 2. At jointing stage and mature stage, water contents of topsoil of different systems were higher than those of NM in three growing seasons. At jointing stage, water content of topsoil of different systems increased by 16.2 %, 23.8 %, and 40.4 %, respectively in 0-20 cm soil layer compared with those of NM in three growing seasons. At mature stage, water content of topsoil of different systems increased by 15.4 %, 15.4 %, and 34.9 %, respectively in 0-20 cm soil compared with those of NM in three growing seasons. In 20-40 cm soil layer, water content of topsoil of different systems increased by 21.1 %, 32.7 %, and 44.3 %, respectively compared with those of NM at jointing stage in three growing seasons, and water contents of topsoil of different systems increased by 14.7 %, 32.5 %, and 45.1 %, respectively compared with those of NM at mature stage in the three growing seasons. In 0-40 cm topsoil layer, water content of soil of different systems increased by 19.6 %, 30 %, and 43 %, respectively compared with those of NM at jointing stage and increased by 15.2 %, 26.8 %, and 41.8 %, respectively at mature stage compared with those of NM in three growing seasons.

Table 2. Water contents of topsoil with the different rainwater harvesting and NM practices at the jointing and mature stages in 2010-2012 (Mean (mm) ± SD). W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots.

Year	Soil layer depth (cm)	Jointing stage				Mature stage			
		NM	**P60**	**M160**	**W80**	**NM**	**P60**	**M160**	**W80**
2010	0-20	14.7±0.7	16.5±0.8	18.3±0.9	20.7±1.2	14.1±1.0	17.5±1.0	23.9±1.2	26.0±0.9
	20-40	30.6±1.2	34.6±1.0	42.0±2.1	42.0±2.1	22.8±1.1	33.0±2.0	41.6±1.7	42.8±2.7
2011	0-20	18.7±0.9	20.1±1.0	22.1±1.1	23.0±1.2	10.7±0.7	12.0±0.6	12.2±0.3	18.6±1.2
	20-40	41.9±2.1	46.3±3.2	54.3±2.7	57.5±2.9	24.7±1.1	25.1±1.6	27.6±1.4	30.6±1.8
2012	0-20	37.0±1.9	45.4±2.3	46.9±2.3	55.1±2.1	27.6±1.6	31.0±1.8	24.5±1.0	26.1±1.7
	20-40	90.8±3.6	116.8±4.7	120.3±8.6	135.9±11.2	50.2±3.3	54.3±4.5	60.5±2.9	68.7±2.4
Mean over the 3 experiment years	0-20	23.5	27.3	29.1	33.0	17.5	20.2	20.2	23.6
	20-40	54.4	65.9	72.2	78.5	32.6	37.4	43.2	47.3
	0-40	77.9	93.2	101.3	111.4	50.0	57.6	63.4	70.9

Soil temperature

Soil temperature in 0-10 cm soil layer is showed in Figure 4 during the proso millet growing seasons. Soil temperatures of different systems and NM were higher than air temperature in three growing seasons. Mean soil temperature of different systems were 0.2°C, 2.1°C, and 2.2°C higher than those of NM at 15 days after sowing in three growing seasons, respectively. Mean soil temperature of different systems increased by 0.3°C, 2.6°C, and 2.7°C compared with those of NM at 30 days after sowing in three growing seasons, respectively. Mean soil temperatures of different systems were 0.1°C, 2.1°C, and 1.8°C higher than those of NM at 45 days after sowing in the three growing seasons, respectively, and mean soil temperatures of different systems were 0.6°C, 2.4°C, and 2.6°C higher than those of NM at 60 days after sowing in three growing seasons, respectively.

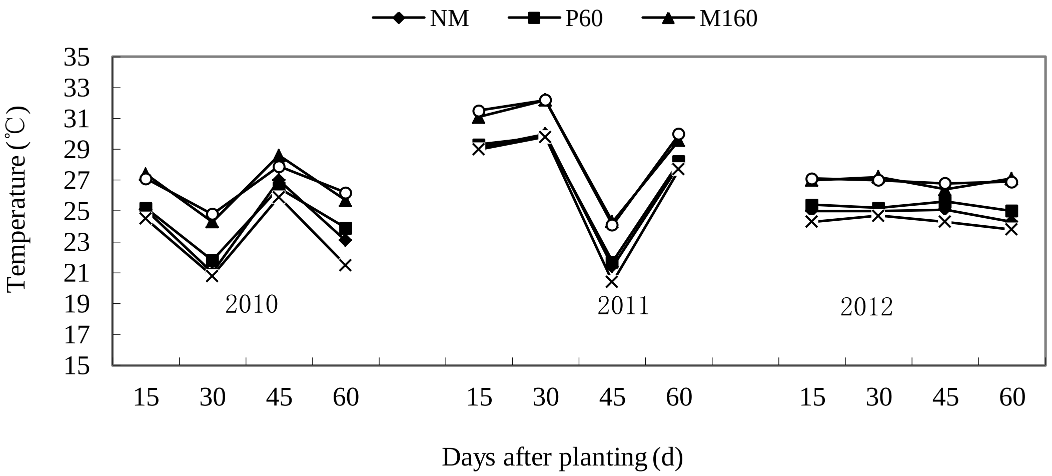

Figure 4. Topsoil temperatures (0-10 cm soil) with the different rainwater harvesting and NM practices in the growing seasons of proso millet from 2010 to 2012. W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots; Air, surface air.

Agronomic traits

Plant height

Plant heights of rainfall harvesting systems are showed in Figure 5. Plant heights of rainfall harvesting systems were significant difference from those of NM ($P<0.05$) in three growing seasons. Plant heights of rainfall harvesting systems at jointing stage increased by 44.7 %, 42.2 %, and 43.2 % in 2010, by 11.6 %, 15.8 %, and 20.2 % in 2011, then by 8.5 %, 20.5 %, and 19.3 % in 2012 compared with those of NM, respectively. Average plant heights based on different rainfall harvesting systems increased by 21.6 %, 26.2 %, and 25.7 % at jointing stage in three growing seasons compared with those of NM, respectively.

At mature stage, plant heights of different rainfall harvesting systems increased by 4.1 %, 14.7 %, and 11.3 % in 2010, by 14.2 %, 10.0 %, and 10.2 % in 2011, then by 4.2 %, 11.9 %, and 10.7 % in 2012 compared with those of NM, respectively. Mean plant heights of rainfall harvesting systems increased by 7.5 %, 12.2 %, and 10.7 % compared with those of NM at mature stage in three growing seasons, respectively.

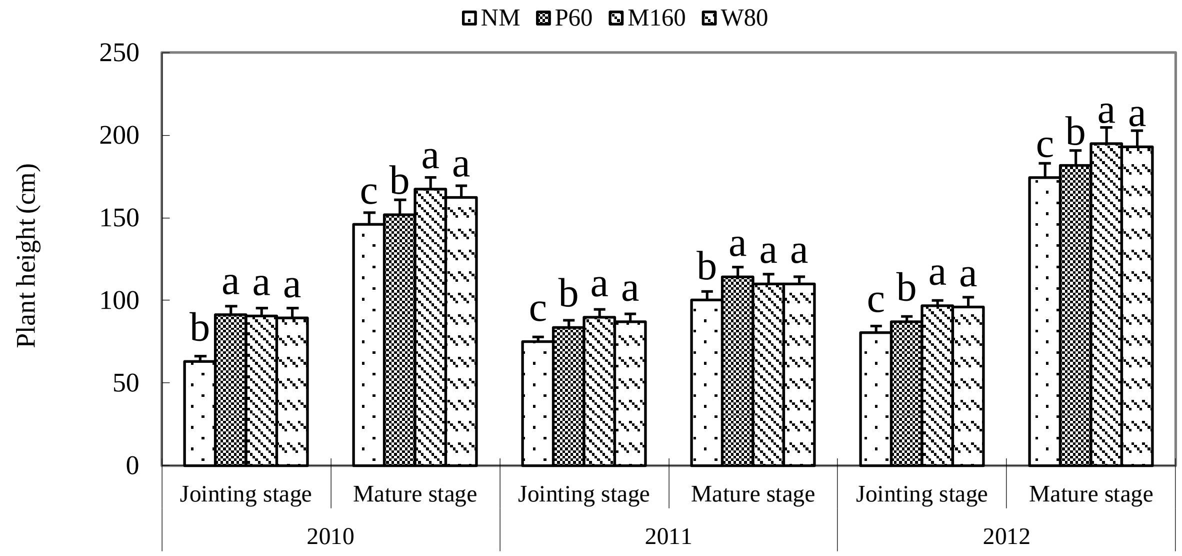

Figure 5. Plant heights with the different rainwater harvesting and NM practices at the jointing stage and mature stages. W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots.

Yield traits

Agronomic traits of yield of proso millet under different rainfall harvesting systems are showed in table 3. In three growing seasons, panicle lengths and branches were difference ($P<0.05$) between rainfall harvesting systems and NM, while No. of main stem and 1000-seed weights was not difference in three growing seasons.

Table 3. Agronomic traits with the different rainwater harvesting and NM practices in 2010-2012 (mean ± SD). W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots. In the same year, different lowercase letters in the same columns indicate significant differences at p=0.05.

Year	Treatment	Node number of main stem (ea)	Panicle length (cm)	Number of panicle branch (ea)	1000-grain weight (g)
2010	P60	7.4±0.5a	35.0±2.0a	14.5±0.8a	9.2±0.4a
	W80	7.3±0.4a	35.3±1.5a	14.0±0.8a	9.2±0.3a
	M160	7.5±0.4a	35.6±1.8a	14.7±0.9a	9.2±0.5a
	NM	7.4±0.3a	33.5±1.7b	12.7±0.4b	9.1±0.5a
2011	P60	6.6±0.3a	33.0±1.9b	14.2±1.0b	8.8±0.4a
	W80	6.9±0.3a	34.3±1.7a	14.3±1.0b	9.1±0.6a
	M160	6.5±0.3a	34.4±1.8a	15.1±0.8a	8.9±0.7a
	NM	6.4±0.4a	32.3±1.4c	13.4±0.6c	8.9±0.7a
2012	P60	3.0±0.1a	43.3±2.4c	7.7±0.4a	8.6±0.4a
	W80	3.0±0.2a	46.3±2.0a	7.7±0.5a	8.6±0.4a
	M160	3.3±0.2a	45.0±2.1b	8.0±0.8a	8.7±0.3a
	NM	3.3±0.2a	41.4±1.7d	7.3±0.5b	8.8±0.6a

Yield of proso millet showed that rainfall harvesting systems had more significant effects on increasing yield of proso millet than those of NM ($P<0.05$) (table 4). In 2010, the rates of increase of yield under different rainfall harvesting systems were 1392 g kg^{-1}, 1719 g kg^{-1}, and 1494 g kg^{-1} compared with those of NM, respectively; In next growing season, the rates of increase of yield of proso millet under different rainfall harvesting systems were 1327 g kg^{-1}, 1503 g kg^{-1}, and 1383 g kg^{-1} compared with those of NM, respectively; In 2012, the rates of yield increased under different rainfall harvesting systems were 185 g kg^{-1}, 238 g kg^{-1}, and 229 g kg^{-1} compared with those of NM, respectively. Yield of different rainfall harvesting systems increased by 968 g kg^{-1}, 1153 g kg^{-1}, and 1035 g kg^{-1} compared with those of NM in three growing seasons, respectively. "W-shaped" system performed best among rainfall harvesting systems and the yield of proso millet with this system increased by 238 g kg^{-1}-1719 g kg^{-1} compared with those of NM and mean rate of yield increase was 1153 g kg^{-1}.

WUE

Water use efficiency under different rainfall harvesting systems significant differed with those of NM in three growing seasons (table 4) ($P<0.05$). In 2010, WUE of different systems increased by 180.0 %, 250 %, and 214 % compared with those of NM, respectively; WUE of different systems increased by 142.3 %, 223.1 %, and 188.5 % compared with those of NM in next growing season, respectively; WUE of different systems increased by 38.7 %, 65.3 %, and 52.0 % compared with those of NM in 2012, respectively. Mean WUE of different rainfall harvesting systems increased by 120.2 %, 179.3 %, and 152.1 % compared with those of NM in three growing seasons, respectively. "W-shaped" system performed best in terms of WUE among different rainfall harvesting systems, and WUE with "W-shaped" system increased by 65.3 %-250 % in three growing seasons as well as mean rate of WUE increase was 179.3 %.

Table 4. Water use efficiencies with the different rainwater harvesting and NM practices in 2010-2012 (mean ± SD). W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots. In the same year, different lowercase letters in the same columns indicate significant differences at p=0.05.

Year	Treatment	Water consumption (0-100 cm) (mm)	Yield ($t\cdot ha^{-1}$)	Yield increase ($g\cdot kg^{-1}$)	Water use efficiency ($t\cdot ha^{-1}\cdot mm^{-1}$)
2010	P60	436.4±20.1	6.1±0.7b	1392	0.0140b
	W80	395.0±18.2	6.9±0.2a	1719	0.0175a
	M160	404.4±20.2	6.4±0.03ab	1494	0.0157ab
	NM	504.9±23.1	2.5±0.04c	-	0.0050c
2011	P60	445.5±22.1	2.8±0.04b	1327	0.0063b
	W80	361.6±17.4	3.0±0.07a	1503	0.0084a
	M160	382.6±19.6	2.9±0.05b	1383	0.0075b
	NM	467.7±24.4	1.2±0.01c	-	0.0026c
2012	P60	300.5±13.0	3.1±0.1a	185	0.0104a
	W80	263.2±13.2	3.3±0.3a	238	0.0124a
	M160	283.5±15.1	3.2±0.08a	229	0.0114a
	NM	350.5±20.5	2.6±0.03b	-	0.0075b

Yield and rainfall

Yield of proso millet with different rainfall harvesting systems at the rainfall (mm) in three growing seasons are showed in Figure 6. Yield of rainfall harvesting system moved up with rainfall (mm) increase in 2010-2011. However, low yield of rainfall harvesting systems were found in 2012 due to lodging. Rainfall (mm) was different in three growing seasons, still yield of proso millet with different rainfall harvesting systems were higher than those of NM. Average yield of proso millet of rainfall harvesting systems and NM tended to quadratic function (Figure 7) with rainfall (mm) variation that showed extreme rainfall (mm) had a negative effect on increasing yield of proso millet under rainfall harvesting system, and three hundred rainfall (mm) of growing season was suitable for rainfall harvesting system in proso millet. Mean increasing rates of yield with rainfall harvesting systems were found significantly linearly correlated with the rainfall (mm) that was explained according to quadratic function (Figure 8) showed that effects of different systems to increase yield of proso millet were limited by abundant rainfall (mm), and 250 mm rainfall of growing season was appropriate for increasing rate of yield.

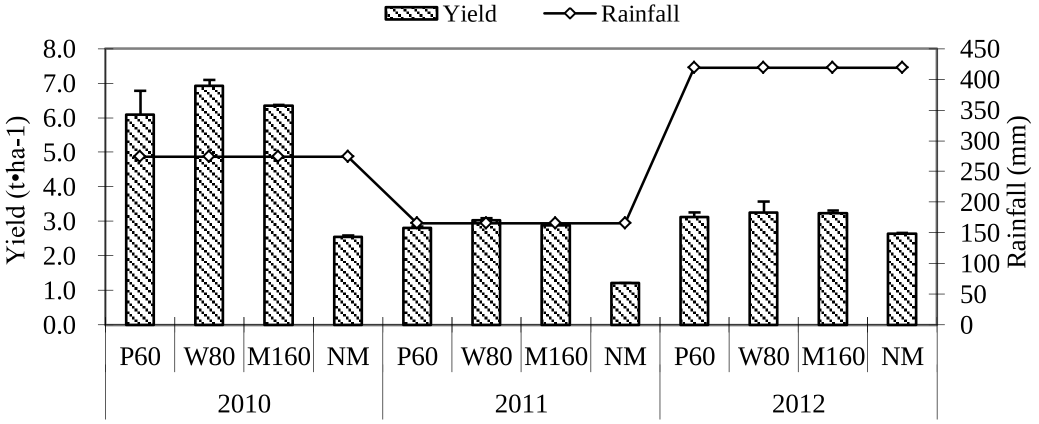

Figure 6. Yields of proso millet and the rainfalls in 2010-2012. W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots.

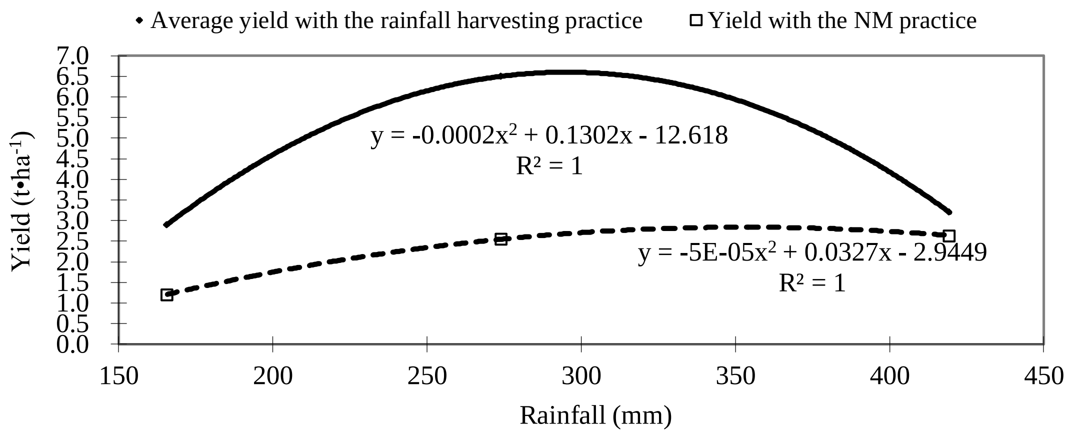

Figure 7. Average yields of proso millet with the different rainwater harvesting and NM practices at the rainfalls (mm). Different rainwater harvesting practices include P60, M160 and W80. W80, the rainwater harvesting practice with 40 cm wide plastic film mulched W-shaped ridges; M160, the rainwater harvesting practice with 100 cm wide plastic film mulched M-shaped ridges; P60, the rainwater harvesting practice with 60 cm wide plastic film mulched ridges; NM, non-mulching plots.

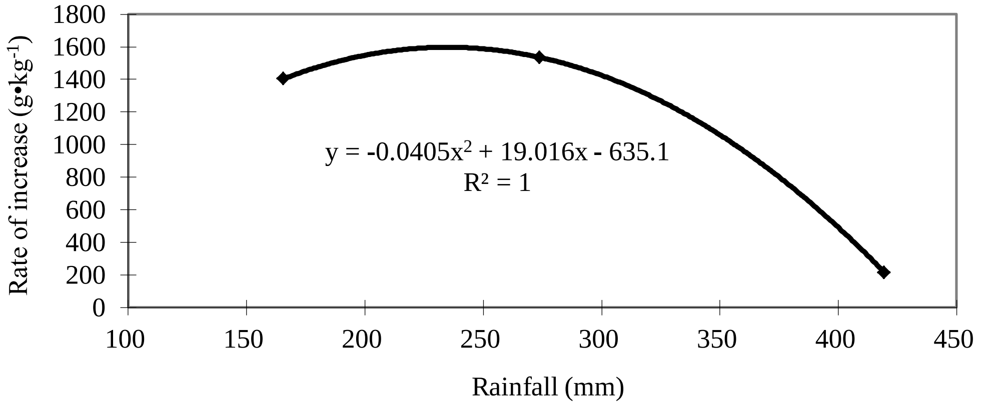

Figure 8. Relations between the mean rates of increase of the yield of proso millet and the rainfalls (mm).

Discussion

Water content of topsoil and temperature of topsoil

Rainfall harvesting systems influenced water content of topsoil and temperature of topsoil and had been suggested as rainfall conservation to improve agricultural productivity where water is scarce for irrigation (J M Miriti et al., 2012). PRFRH system could improve rainfall utilization and increase water content of topsoil and temperature of topsoil (Xianglin Li et al., 2007; Hong et al., 2012). In this study, rainfall harvesting systems could increased water content of topsoil with performing better on 20-40 cm soil layer than on 0-20 cm soil layer, and increased soil water content at jointing stage more than those at mature stage due to water evaporation which might result from degraded or broken plastic film of later stage. For soil temperature, mean daily soil temperature of 10 cm soil depth of different systems and NM were always higher than air temperature, and mean daily soil temperature of different systems was higher than those of NM at the measurement-involved stage. These results showed rainfall harvesting systems played an important factor in increasing water content of topsoil and temperature of topsoil (Gao and li, 2005; Xiao et al., 2010; Hong et al., 2012; Wang et al., 2013), and this result supported hypotheses tested. "W-shaped" systems performed best among all rainfall harvesting systems.

3.2 Growth stage with best performances of the rainfall harvesting systems

High water content of topsoil and temperature of topsoil were necessary for seed germination and crop growth (Gelmond, 1978; Li et al., 1999; Luan et al., 2001). Rainfall harvesting systems increased water content of topsoil and temperature of topsoil, which are sufficient advantage for improving proso millet growth. In this study, increase rates of plant height of rainfall harvesting systems at jointing stage were higher than those at mature stage. Rainfall harvesting systems, therefore, probably had better effects on improving early growth of proso millet than later growth. In this regard, potato was researched and to obtain similar results (Hong et al., 2012 and Xiao et al., 2010).

The optimal rainfall harvesting system

In arid and semi-arid regions, rainfall harvesting systems based on plastic mulch could increase water content of soil and crop yield (Deng et al., 2006), and there are optimal rainfall harvesting systems for different crops reported in recent years. The optimal rainfall harvesting systems with furrow and plastic film mulched ridges of different crops were 60 cm wide furrows and 60 cm wide ridges (maize, alfalfa and millet) (Li and Gong, 2002; Li et al., 2007; Qu et al., 2012) and ones with 45 cm wide furrows and 60 cm wide ridges (potato) (Tian et al., 2003). In this study, rainfall harvesting systems increased yield and WUE of proso millet compared with those of NM, and high yield and WUE were found in "W-shaped" systems. Mean rates of yield increase and mean rate of WUE increase with "W-shaped" systems were higher ($P < 0.05$) than those of other systems and NM. "W-shaped" system performed better in increasing water content of topsoil, temperature of topsoil and yield of proso millet than "P60" system. "W-shaped" system was an optimal rainfall harvesting system of proso millet in semi-arid regions, meet objective of this study.

Limiting factor of rainfall harvesting system

Rainfall harvesting system has suitable regions and reported to be limited use in regions of less than 250 mm annual rainfall (Li, 1998; Ben et al., 1987; Boers et al., 1986a, 1986b, 1982). For simulated rainfall conditions, abundant rainfall (mm) limited yield increasing effect of rainfall harvesting practices (Xiao et al., 2008). In this study, lodging of proso millet was found in 2012, which may result from that rainfall was so too many that vegetative growth of proso millet was excessive. Besides, Figure 7 and Figure 8 showed further relationship between rainfall (mm) and yield traits. Figure 8 showed that rainfall harvesting systems performed the best effect on yield of proso millet with about 300 mm growth rainfall, and it was over 250 mm rainfall that was found to prevent rainfall harvesting system from increasing the rates of moving up in the yield of proso millet (Figure 7). Yield increasing effects of rainfall harvesting systems, therefore, were limited by abundant rainfall (mm) that was found in maize (Ren et al., 2008) in simulated rainfall conditions and performed the best affection with 250 mm-300 mm rainfall during growing seasons of proso millet in semi-arid regions. Although limiting factor of rainfall harvesting system was found in the field to some extent, further research was still needed due to less test seasons.

Conclusion

Rainfall harvesting systems based on furrows and plastic film-mulched ridges could increase water content of topsoil, move up in temperature of topsoil, and improve growth, yield and WUE of proso millet, respectively. Abundant rainfall (mm) was a limited factor for increasing rate of yield of proso millet under rainfall harvesting system. Rainfall harvesting systems performed better in improving early growth and yield formation of proso millet. About 250 mm-300 mm rainfall during growing season of proso millet was right for rainfall harvesting system. "W-shaped" system was suitable for increasing yield of proso millet in semi-arid areas.

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