Effects of Rainfall Harvesting and Mulching Technologies on Water Use Efficiency and Crop Yield in the Semi-arid Loess Plateau, China

Zhongkui Xie[1], Yajun Wang[1*], Sukhdev S. Malhi[2], Cecil Vera[2], Yubao Zhang[1] and Jinniu Wang[1]

[1]Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou 730000, China (*Correspondence: w.yajun@yahoo.com)

[2]Agriculture and Agri-Food Canada, Research Farm, P.O. Box 1240, Melfort, Saskatchewan, Canada S0E 1A0

Background

- In the northwest Loess Plateau of China with mean annual precipitation ranging between 250 and 350 mm, soil moisture is generally limited and crop growth is stressed by drought during the growing season, resulting in decreased and unsustainable crop yields.
- In this semi-arid region with low rainfall, for optimum crop growth and yield irrigation is needed.
- But in most sloping fields, crops are grown under rainfed conditions. In addition, some irrigated crops are also forced to cease irrigation or reduce irrigation times to restrict irrigation amount due to high costs.
- Recent research has shown that some practical techniques, such as methods of rainwater harvesting and supplementary irrigation, can be used to improve crop yields and production stability of the farmland ecosystem.
- There is limited information on this techniques for this low precipitation area.

Objective

- To determine the influence of ridge and furrow rainfall harvesting system (RFRHS), surface mulching and supplementary irrigation in various combinations on rainwater harvesting, amount of moisture in soil, water use efficiency (WUE), and biomass yield of sweet sorghum (*Sorghum bicolour* L.) or seed yield of maize (*Zea mays* L.).

Materials and Methods

- Field experiments were conducted in 2005 and 2006 at the Gaolan Research Station, Chinese Academy of Sciences, Gansu, China.
- For sweet sorghum, there were 8 treatments (1 to 8) in 2005 and 10 treatments in 2006: (1) plastic-mulched field at planting (conventional; PMFd); (2) plastic-mulched field at planting plus supplementary irrigation 30 mm under the film (PMFd-SI30); (3) plastic-mulched planting plus supplementary irrigation 60 mm under the film (PMFd-SI60); (4) RFRHS with plastic-covered ridge and bare furrow (RFRHS-PCR-BFr); (5) RFRHS with plastic-covered ridge and plastic-mulched furrow (RFRHS-PCR-PMFr); (6) RFRHS with bare ridge and plastic-mulched furrow (RFRHS-BR-PMFr); (7) RFRHS with plastic-covered ridge and gravel-sand-mulched furrow (RFRHS-PCR-GMFr); (8) RFRHS with plastic-covered ridge and plastic-mulched furrow plus supplementary irrigation 30 mm (RFRHS-PCR-PMFr-SI30); (9) RFRHS with

plastic-covered ridge and plastic-mulched furrow plus supplementary irrigation 90 mm (RFRHS-PCR-PMFr-SI60); and (10) gravel-sand-mulched field in 8 cm thickness (GMFd).

- For maize, there were 11 treatments: (1) plastic-mulched field at planting (conventional; PMFd); (2) straw-mulched field during the emergence period (SMFd); (3) gravel-sand-mulched field in 8 cm thickness (GMFd); (4) RFRHS with plastic-covered ridge and bare furrow(RFRHS-PCR-BFr); (5) RFRHS with plastic-covered ridge and straw-mulched furrow during the emergence period (RFRHS-PCR-SMFr); (6) RFRHS with plastic-covered ridge and gravel-sand-mulched furrow (RFRHS-PCR-GMFr); (7) RFRHS with plastic-covered ridge and bare furrow plus supplementary irrigation 30 mm during the bloom stage (RFRHS-PCR-BFr-SI30); (8) RFRHS with plastic-covered ridge and straw mulched furrow during the emergence period plus supplementary irrigation 30 mm during the bloom (RFRHS-PCR-SMFr-SI30); (9) plastic-mulched field plus supplementary irrigation 30 mm under the film (PMFd-SI30); (10) plastic-mulched field plus supplementary irrigation 60 mm under the film (PMFd-SI60); and (11) plastic-mulched field plus supplementary irrigation 90 mm under the film (PMFd-SI90).
- Gravimetric soil water content was measured at 10 cm intervals in the 0-40 cm soil depth, and at 20 cm intervals in the 40-160 cm soil depth.
- Soil water evaporation was measured using micro-lysimeters.
- The amount of the rainfall was recorded using a standard rain gauge.
- Evapotranspiration (ET) was determined by the following formula: $ET = \Delta W + P + I - D$. Where ΔW is the change in soil water storage (mm) between planting and harvest period or growth stages, P is the crop growing season precipitation, I is the amount of irrigation (mm) that was measured using a water meter, and D is the amount of water lost due to deep drainage, which was negligible in this study.
- Water use efficiency (WUE) was calculated as kg of biomass yield produced per mm^{-1} of water available for crop use.
- At harvesting in 2005, we dug a soil profile for all mulched treatments to characterize maize rooting patterns (root length and mass).
- In 2006, we compared differences in runoff efficiency between RFRHS with plastic-covered ridge and RFRHS with bare ridge. We collected the runoff water and calculated runoff efficiency for these two treatments after each rainfall.

Summary and Conclusions

Precipitation (Table 1)

- There was no effect of RFRHS without plastic-covered ridge on rainwater harvesting for natural precipitation of less than 5 mm per event. This is because there is little water runoff from frequent low precipitation showers in this area, and most of the harvested rainwater gather on the soil surface, resulting in increased evaporation.

Water Runoff Efficiency (Table 2)

- For the no plastic covered ridge treatments, only in two out of 10 instances any measurable runoff was detected, when rainfall of 4.6 mm and 11.6 mm was recorded. In those two rainfall events, the runoff efficiency was only 5.7% and 5.5%, which was much lower than the corresponding values of 40.5% and 34.2% for plastic-covered ridge, clearly showing the positive impact of plastic mulch in increasing the amount of rainwater harvesting.

Water Evaporation (Table 3)

- Soil water evaporation was lowest for mulching with gravel-sand, and was highest for non-mulching treatment, suggesting significantly more water loss from soil and subsequently less water available for crop use in the growing season in the non-mulched plots.

Root Length Density (Figure 1)

- The percentage of root length density (RLD) in the 50 cm depth was highest (83.6%) for mulch plus SI 90 mm, followed closely by 82.3% for RFRHS with straw-mulch plus SI 30 mm, and was lowest (56.6%) for RFRHS with gravel-sand mulch. This suggests that RFRHS with gravel-sand mulch could make the roots to develop deeper.

Crop Yield and Water Use Efficiency (Tables 4, 5, 6 and 7)

- In the conventional fields without RFRHS, gravel-sand mulched fields produced higher crop yield than plastic-mulched or straw-mulched fields.
- In the plastic-mulched fields, increasing amount of supplemental irrigation was needed to improve crop yield. In the RFRHS, yield and WUE were higher with plastic-covered ridge than bare ridge, and also higher with gravel-sand-mulched furrow than bare furrow in most cases, or straw-mulched furrow in some cases. This was most likely due to decreased evaporation with plastic or gravel-sand mulch, resulting in increased WUE and crop growth.
- In the RFRHS with plastic-covered ridge and gravel-sand-mulched furrow, application of 30 mm supplemental irrigation produced the highest yield and WUE for maize and sweet sorghum in most cases.

Comparisons of Costs for Different RFRHS Systems (Tables 8, 9 and 10)

- The estimated costs were 4964 Yuan ($709) ha^{-1} and 6596 Yuan (942) ha^{-1} for conventional practice (PMFd) with mulch plus irrigation 60 mm and 90 mm, respectively, and this was considerably higher than all RFRHS treatments.

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Table 1. Annual rainfall characteristics from April to September in 2001 to 2006 at the experimental site Gaolan, Gansu, China

Year	Rainfall times (T)	Rainfall (<5 mm) times (RT)	RT/T (%)	Total amount (A) (mm)	Rainfall (<5mm) amount (RA) (mm)	RA/A (%)
2001	38	23	60.5	239	53	22.0
2002	28	12	42.9	241	30	12.6
2003	38	25	65.8	278	69	24.8
2004	32	19	59.4	187	36	19.4
2005	44	31	70.5	170	58	34.2
2006	46	34	73.9	229	66	28.9

Table 2. Comparisons of runoff efficiency (RE) of rainwater between ridge and furrow rainfall harvesting systems (RFRHS) with plastic-covered ridge and bare ridge in a field without crop at Gaolan, Gansu, China in 2006

Date	Rainfall (mm)	RE (%)		
		Plastic-covered ridge (PCR)	Bare ridge (BR)	Difference between PCR and BR
July 27	11.6	34.2	5.5	+28.7**
July 30	3.6	10.6	0.0	+10.6**
August 2	0.4	29.1	0.0	+29.1**
August 6	1.7	28.7	0.0	+28.7**
August 11	3.2	36.9	0.0	+36.9**
August 16	4.6	40.5	5.7	+34.8**
August 22	1.1	36.4	0.0	+36.4**
August 29	0.9	25.0	0.0	+25.0**
August 31	4	39.1	0.0	+39.1**
September 5	2.4	28.7	0.0	+28.7**
Mean		30.9	1.1	+29.8**

** refers to significant treatment effect for RE in paired t-test at $P \leq 0.01$.

Table 3. Comparisons of evaporation of water from soil among different mulching patterns in ridge and furrow rainfall harvesting system **(**RFRHS) in maize from August to September at Gaolan, Gansu, China in 2006

Treatments	Amount of water evaporation from soil (mm)		
	Foot of the ridge	1/4 of the furrow	1/2 of the furrow
RFRHS-PCR-SMFr	0.53	0.56	0.54
RFRHS-PCR-GMFr	0.47	0.35	0.32
RFRHS-PCR-BFr	0.76	0.67	0.62

Table 4. Total water use, water use efficiency (WUE) and biomass yield of sweet sorghum, with different water use and water harvest treatments at Gaolan, Gansu, China in 2005.

Treatments†	Irrigation depth (I) (mm)	Change in soil water content during growing season (ΔW) (mm)	Total water use (ET) (mm)	Biomass yield (kg ha^{-1})	WUE (kg mm^{-1})
1 PMFd	0	65.5	229	6581	28.7
2 PMFd-SI30	30	53.0	247	10464	42.4
3 PMFd-SI60	60	46.7	271	9986	36.9
4 RFRHS-PCR- BFr	0	56.3	220	9135	41.5
5 RFRHS-PCR- PMFr	0	66.4	230	9948	43.2
6 RFRHS-BR-PMFr	0	46.3	210	6331	30.1
7 RFRHS-PCR-GMFr	0	35.8	200	8892	44.5
8 RFRHS-PCR-PMFr-SI30	30	36.7	230	11135	48.4
$LSD_{0.05}$			ns	2241**	12.2*

*, ** and ns refer to significant treatment effect in ANOVA at $P \leq 0.01$, $P \leq 0.05$ and not significant, respectively.
Precipitation in the growing season was 164 mm.

Table 5. Total water use, water use efficiency (WUE) and biomass yield of sweet sorghum, with different water use and water harvest treatments at Gaolan, Gansu, China in 2006.

Treatments	Irrigation depth (I) (mm)	Change in soil water content during growing season (ΔW) (mm)	Total Water Use (ET) (mm)	Biomass yield (kg ha^{-1})	WUE (kg mm^{-1})
1 PMFd	0	84.6	285	7808	27.4
2 PMFd-SI30	30	88.1	318	9076	28.5
3 PMFd-SI60	60	97.8	358	10022	28.0
4 RFRHS-PCR-BFr	0	100.6	301	10262	34.1
5 RFRHS-PCR-PMFr	0	117.2	317	7935	25.0
6 RFRHS-BR-PMFr	0	94.4	295	7213	24.5
7 RFRHS-PCR-GMFr	0	107.3	308	9364	30.5
8 RFRHS-PCR-PMFr-SI30	30	95.8	326	11796	36.2
9 RFRHS-PCR-PMFr-SI60	60	85.0	345	11351	32.9
10 GMFd	0	116.1	316	10511	33.2
$LSD_{0.05}$			32**	2568**	ns

** and ns refer to significant treatment effect in ANOVA at $P \leq 0.01$ and not significant, respectively.
Precipitation in the growing season was 200 mm.

Table 6. Total water use, water use efficiency (WUE) and biomass yield of sweet maize, with different water use and water harvest treatments at Gaolan, Gansu, China in 2005.

Treatments	Irrigation depth (I) (mm)	Change in soil water content during growing season (ΔW) (mm)	Total Water Use (ET) (mm)	Biomass yield (kg ha^{-1})	WUE (kg mm^{-1})
1 PMFd	0	90.6	241	1474	6.1
2 SMFd	0	102.0	252	1029	4.0
3 GMFd	0	104.1	254	2322	9.2
4 RFRHS-PCR-BFr	0	107.9	258	2382	9.1
5 RFRHS-PCR-SMFr	0	103.6	254	3047	11.8
6 RFRHS-PCR-GMFr	0	48.6	199	2799	14.1
7 RFRHS-PCR-BFr-SI30	30	75.5	256	3325	13.2
8 RFRHS-PCR-SMFr-SI30	30	89.1	269	2445	9.1
9 PMFd-SI30	30	118.1	298	2456	8.2
10 PMFd-SI60	60	79.6	290	4172	14.4
11 PMFd-SI90	90	72.6	313	6050	19.4
$LSD_{0.05}$			58*	1191**	5.3**

* and ** refer to significant treatment effect in ANOVA at $P \leq 0.05$ and $P \leq 0.01$, respectively.
Precipitation in the growing season was 150 mm.

Table 7. Total water use, water use efficiency (WUE) and biomass yield of sweet maize, with different water use and water harvest treatments at Gaolan, Gansu, China in 2006.

Treatments	Irrigation depth (I) (mm)	Change in soil water content during growing season (ΔW) (mm)	Total Water Use (ET) (mm)	Biomass yield (kg ha^{-1})	WUE (kg mm^{-1})
1 PMFd	0	40.7	255	551	2.1
2 SMFd	0	45.6	260	199	0.8
3 GMFd	0	66.3	281	1382	5.0
4 RFRHS-PCR-BFr	0	43.1	258	1124	4.3
5 RFRHS-PCR-SMFr	0	52.0	267	694	2.7
6 RFRHS-PCR-GMFr	0	68.4	283	3129	10.9
7 RFRHS-PCR-BFr-SI30	30	40.6	285	2332	8.1
8 RFRHS-PCR-SMFr-SI30	30	71.8	317	2961	9.1
9 PMFd-SI30	30	39.1	284	1397	4.9
10 PMFd-SI60	60	47.5	322	2270	7.0
11 PMFd-SI90	90	61.4	366	2383	6.5
$LSD_{0.05}$			39**	961**	2.9**

** refer to significant treatment effect in ANOVA at $P \leq 0.01$.
Precipitation in the growing season was 215 mm.

Table 8. Costs and runoff efficiency of rainwater for different catchment ways at Gaolan, Gansu, China

Catchments	Annual runoff efficiency (%)	Cost of preparing for harvesting rainwater		Cost for rainwater harvesting based on 300 mm annual rainfall	
		Yuan m^{-2}	\$ ha^{-1}	Yuan m^{-3}	\$ m^{-3}
Cleared loess slope	12.5	0.08	114	2.13	0.30
Roof of greenhouse	85.0	0.05	71	0.22	0.03
Old plastic mulch surface	66.6	0.05	71	0.25	0.04
Road	75.0	0.05	71	0.22	0.03
Roof of house	58.3	0.05	71	0.29	0.04

Table 9. Storage costs of rainwater harvesting for different storage tank at Gaolan, Gansu, China

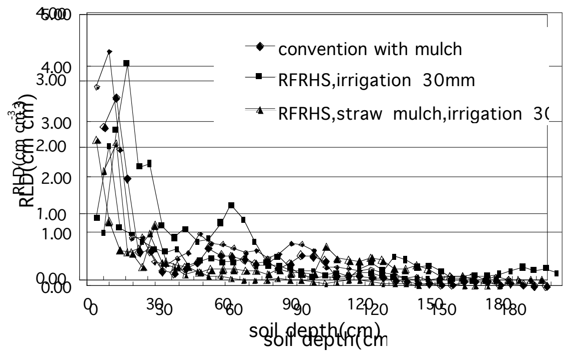
Tank types	Storage capacity (m^3)	Service life (yr)	Cost of building tanks (Yuan/\$)	Storage cost† (Yuan m^{-3}/\$ m^{-3})
Sand-soil-plastic storage tank	25	5	414 (59)	3.31 (0.47)
Concrete tank with thin wall	25	8	820 (117)	4.10 (0.59)
Clay tank	50	8	1640 (234)	4.10 (0.59)
Big concrete tank	100	15	9600 (1371)	6.40 (0.91)
Concrete tank	25	15	2500 (357)	6.67 (0.95)

†Storage cost= Total cost/storage capacity × service life.

Table 10. Comparisons of costs between ridge and furrow rainfall harvesting system (RFRHS) and mulch surface at Gaolan, Gansu, China

Catchments	Annual labor cost† (Yuan/\$ ha^{-1})	Annual cost for mulch materials (Yuan/\$ ha^{-1})	Total annual cost (Yuan/\$ ha^{-1})
Conventional field (without RFRHS)	1200 (171)	0 (0)	1200 (171)
RFRHS with plastic mulch ridge	1800 (257)	900 (129)	2700 (386)
RFRHS with plastic-covered ridge and furrow	1800 (257)	1440 (206)	3240 (463)
RFRHS with plastic-covered ridge and straw- mulched furrow	1800 (257)	1350 (193)	3150 (450)
RFRHS with plastic-covered ridge and gravel-sand-mulched furrow	1800 (257)	1575 (225)	3375 (482)

†Labor cost is 20 Yuan per one, the cost for gravel-sand is 90 yuan m^{-3}, plastic is 12 yuan kg^{-1} and the cost for straw is 0.15 Yuan kg^{-1}.



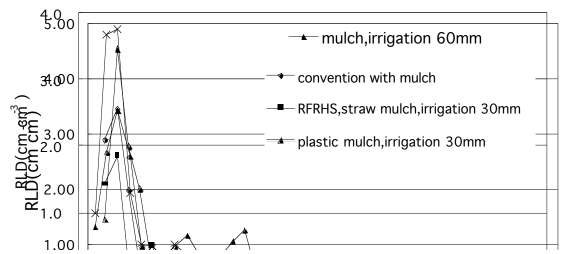


Figure 1. Root length density (RLD) in different treatments for maize in 2005 at Gaolan, Gansu, China