**Optimum ridge-furrow ratio and suitable ridge-mulching
material for Alfalfa production in rainwater harvesting in
semi-arid regions of China**

**Qi Wang¹, Xingyang Song¹, Fuchun Li¹, Guangrong Hu¹,
Qinglin Liu², Enhe Zhang², Heling Wang³, Roger Davies⁴**

(1. College of Grassland Science, Gansu Agricultural University, Lanzhou 730070, China; 2. Agronomy College, Gansu Agricultural University, Lanzhou 730070, China; 3. Key Laboratory of Arid Climatic Change and Reducing Disaster of Gansu Province, Key Open Laboratory of Arid Change and Disaster Reduction of CMA, Institute of Arid Meteorology, China Meteorological Administration, Lanzhou 730020, China; 4. New Zealand China Friendship Society, Christchurch, New Zealand)

Abstract: Alfalfa (*Medicago sativa* L) is traditionally sown in field without ridge and furrow, in rain-fed semi-arid areas of Northwest China, and forage yields are normally low because of drought, water loss and soil erosion. A field study was conducted to determine 1) Monthly runoff efficiency and threshold rainfall for different ridge widths (30, 45 and 60 cm), and mulched with different materials (common plastic film, bio-degradable mulching film and manually compacted soil); and 2) the effects of different ridge-furrow ratios (30:60, 45:60 and 60:60) and ridge-mulching materials on soil water storage, topsoil temperature, forage yields, and water use efficiency (WUE) of Alfalfa in ridge-furrow rainwater harvesting (RFRWH) system, during 2 consecutive years: 2012 and 2013. Average monthly runoff efficiency over these 2

Received date: ; Accepted date:

Biography: Q Wang, PHD, Email: wangqigsau@gmail.com, Phone: (86)13893339925

years, was 16%, 18%, 19%, 65%, 71%, 77%, 70%, 72% and 79% for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ (SR, BMR and CMR were ridges with manually compacted soil, mulched with bio-degradable mulch film and common plastic film, respectively, and subscripts 30, 45 and 60 refer to ridge widths (cm) all with 60 cm furrow width), respectively. For the same treatments, threshold rainfall was 4.3, 4.3, 4.2, 3.0, 2.9, 2.8, 2.9, 2.9 and 2.8 mm. The field experiment showed that ridge mulching materials and ridge widths had distinct effects on topsoil temperature at ridge tops, but not at furrow bottoms. Soil water storage in 140 cm soil depth at furrow bottoms increased with increasing ridge width and in the order of CMR $\approx$ BMR > SR > FP. Average annual total forage yields for FP, SR, BMR and CMR were 6276, 5642, 7563 and 7817 kg ha⁻¹, respectively, over 2 years. The total precipitation in both years was higher than average of rainfall, leading to significant decreases of forage yields for SR, and significant increases of forage yields for BMR and CMR. Compared with FP, average forage yields decreased by 3%, 10% and 17% for SR₃₀, SR₄₅ and SR₆₀, and increased by 27%, 21%, 13%, 32%, 26% and 16% for BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, over 2 years. WUE for SR, BMR and CMR was 1.69, 1.74 and 1.74 times greater than that for FP over 2 years, and increased with decreasing ridge width. Optimum furrow width was 35-36 cm for CMR and BMR in the RFRWH system with 60 cm width furrows for Alfalfa production in this region. Future study is needed to investigate optimum ridge-furrow ratio and suitable ridge-mulching material for achieving the best environmental and economic benefit under different climatic conditions, soil types and plant species, and using bio-degradable mulching materials.

Keywords Rainwater harvesting, furrow, ridge, runoff, forage yield, water use efficiency

Abbreviations

SR: ridge compacted with soil; BMR: ridge mulched with bio-degradable mulch film; CMR: ridge mulched with common plastic film; FP: flat planting; WUE: water use

efficiency; RFRWH: Ridge-furrow rainwater harvesting; FY: forage yields; ET: evapotranspiration; ANOVA: analysis of variance.

1 Introduction

Semi-arid regions are characterized by low and irregular precipitation, water loss, soil erosion, high evaporation, and low vegetative coverage and desertification, which is a global ecological and environmental problem caused by climate change and human activities. The majority of the subsistence farmers in this region depend on rain-fed agriculture and pastoralism, but the agriculture and pastoralism harvests are likely to be irregular (Zhao et al., 2014). Food security has been made worse by spring cold and drought, as well as strong winds, thunderstorms, and hail in summer in the middle of the Loess Plateau in Gansu Province (Shan & Chen, 1993). Most rainfall is low intensity (< 5 mm) and cannot be utilized by crops, while a few rainfall events occur as a result of intensive storms which are not absorbed by soil, and produce runoff. The drought and extreme climates in this region have become more serious with global warming in recent years (Qin et al., 2002, Zhao et al., 2005). Due to drought, simple cropping program and the fragility of loess soil, the ecology of this semi-arid region is vulnerable to degradation of vegetation, water loss, and soil erosion and desertification. In this region with limited surface water resource availability, the only option for increasing agricultural production and sustainable development is to increase rainwater use efficiency through rainwater harvesting and mulching.

In order to alleviate food scarcity, many management strategies have been used to improve rainwater use efficiency in this region, such as ridge-furrow rainwater harvesting (RFRWH), terracing, Jessour system, V shaped bunds, and semicircle bunds (Gupta et al., 1999; Zhao et al., 1995; Zhang et al., 2013), mulching using plastic film, hay, wood chips, wood fibers, straw, gravel, sand, etc (Li et al., 2002). RFRWH usually consists of alternate ridges and furrows dug along contours. Mulched

ridge is usually used for rainwater harvesting zone, and mulched or non-mulched furrow is usually used for planting zone. This method is one of the most efficient technical applications for maximizing rainfall utilization, especially light rainfall in semi-arid regions (Deng et al., 2006). The RFRWH collects runoff from ridges, and rainwater coupled runoff in furrows, leading to deep soil water infiltration, and reduced water loss and soil erosion (Boers et al., 1986). In this region, the RFRWH system, especially alternating large and small ridges using full mulching, has played a significant role in maize (*Zea mays* L.) production. Mulching on ridges can reduce soil evaporation and increase topsoil temperature. The major disadvantage of the RFRWH system is labor cost and planting area reduction (Janette W. & Tim, H., 2006), while major advantages are soil and water conservation, improvement of soil moisture, topsoil temperature, soil nutrient availability, and prolonged growing seasons leading to an increase in agricultural production (Gupta, 1995; Li et al., 2000a; 2000b; Jia et al., 2006). Further, the RFRWH system has become a valuable technique for suppressing weeds and insect pests, and for improving cold tolerance (Liu et al., 2009). Optimum ridge-furrow ratio was different for different plant species under different climatic conditions and soil types. The prior research (Wang et al., 2008) found that optimum ridge-furrow ratio was 39-48 cm for potato production in this region. Zhao et al. (2002) showed that potato tuber yields were increased by 57.4-78.2% with RFRWH, while WUE was increased by 56.8-70.3%, compared with traditional cultivation without ridge and furrow, and mulching.

Common plastic film is a major mulching material in this region, and does not be bio-degrade readily in the field. Large amounts of residual plastic film have a detrimental effect on soil structure, water and nutrient transport and crop growth, and animal health. Thereby the residual plastic film disrupts agricultural environment and reduces crop production (Moreno et al., 2008; Liu et al., 2014). There is currently no treatment available to solve this problem, and a lack of research on the application of new biodegradability films.

Alfalfa (*Medicago sativa* L) is the perennial forage with the largest planted area in Northwest China, due to its high crude protein content, hay yield, drought-resistance, and adaptation to various climatic and soil conditions (Wan et al., 2004). Alfalfa cultivation contributes to soil and water conservation, and nitrogen fixation (Li et al., 2007), but requires more water than other crops, leading to a distinctive and permanent dry layer within root zone. Water scarcity is the most limiting factor for expanding Alfalfa production in this region (Zhao et al., 2004; Al-Rumikhani, 2002). High water consumption by Alfalfa can reduce soil moisture, leading to further ecological deterioration in the region. It is therefore important to find optimum ridge-furrow ratio and suitable ridge-mulching material for Alfalfa production in the RFRWH system.

2 Materials and methods

2.1 Climate and soil characteristics

Field experiments were conducted at Dingxi Arid Meteorology and Ecological Environment Experimental Station of the Institute of Arid Meteorology of China Meteorological Administration during 2 consecutive Alfalfa growing seasons: 2012 and 2013. The experimental station (latitude of 35°35'N, longitude of 104°37'E, and an altitude of 1896.7 m asl) lies in Dingxi city, Gansu Province, Northwest China. The climate is of medium temperate and semi-arid with mean annual air temperature of 7.2 °C, mean annual maximum and minimum air temperatures of 25.9 °C (July) and -13.0 °C (January). Mean annual precipitation was 388 mm (average values for 1971-2013), and around 56% of the precipitation occurs between July and September. The potential annual evaporation is about 1445mm. Mean annual sunshine exceeds 2438 h, and frost-free period is about 140 d ranging from 99 d to 183 d. The monthly mean air temperature and precipitation over the last 43 years showed a pattern of simultaneous heat and moisture. The soil at the experiment site is a loess-like loam with an average bulk density of 1.38 g cm⁻³ before sowing, and a field water holding

capacity of 25.6%. The permanent wilting point in 140 cm depth soil profile is 6.7% according to data from the Agri-Meteorological Station. The physical and chemical properties of the soil are presented in Table 1. The farming practices were monoculture with crops harvesting only once in a year because of lack of heat and low temperature. Major crops are spring wheat (*Triticum aestivum* L), maize, oat (*Avena sativa* L), faba beans (*Vicia faba*), potato (*Solanum tuberosum*), millet (*Panicum miliaceum*) and oriental sesame (*Sesamum indicum*), and major forages are Alfalfa and Sainfoin (*Onobrychis viciaefolia*).

2.2 Experimental design

2.2.1 Runoff observation

Runoff plots, near Alfalfa growing plots, were constructed for measuring monthly runoff efficiencies for different ridge mulching materials and ridge widths (Fig 1). Three ridge mulching materials were common plastic film, bio-degradable mulching film and manually compacted soil. Three ridge widths were 30, 45 and 60 cm. CMR, BMR and SR were abbreviated for ridges mulched with common plastic film, bio-degradable mulch film and manually compacted soil. The common plastic film and bio-degradable mulch film were mulched on ridges surface with edges buried under in 3-5cm depth soil along bases of ridges. Manually compacted soil was made by hands during ridges banking, and became soil crust later after rainfalls. The thickness of the common plastic film and the bio-degradable mulching film was 0.008 mm. The common plastic film was manufactured by Shijiazhuang Yongsheng Plastic Plant Co Ltd, China, and bio-degradable mulch film was manufactured by BASF Co Ltd, Germany. The bio-degradable mulch film was composed of starch and other bio-materials. There were 9 treatments (3 ridge widths $\times$ 3 ridge-mulching materials) with 3 replications in a complete randomized arrangement. Ridge height was about 20 cm, and ridge surface was arched with an about 40° slope angle. Each replication was a 10 m long ridge with a bucket. A cement block border, 8 cm high, was installed around ridges to collect runoff and to divert runoff through 2 hoses into a bucket.

Asphalt was sprayed on the surface of soil at the bases of ridges to prevent runoff permeating into soil. Water-buckets, covered with lids with 2 small holes to prevent them from collecting precipitation and to prevent evaporation of collected runoff, were placed at the ends of the 2 water hoses and installed in a 2 meters deep field trench with its lids below ground surface. A 250 liter volume water bucket was used for CMR and BMR, and a 150 liter volume water bucket was used for the SR.

2.2.2 Alfalfa production

RFRWH was prepared by shaping soil surface into alternate ridge and furrow. There were 10 treatments (3 ridge widths $\times$ 3 ridge-mulching materials + flat planting (FP) as control) with 3 replications in a completely randomized arrangement. The 3 ridge (side-slopes of 40° and 20 cm high) widths were 30, 45 and 60 cm, respectively, with 60 cm furrow width for all treatments. The size, shape and ridge-mulching materials in Alfalfa production experiment were the same as those in the runoff observation experiment. The mulched ridges served as rainwater harvesting zones, and the non-mulched furrows served as planting zones. Individual plots, 10 m long and 3.0-4.2 m wide, had 4 ridges and 3 furrows, except for the controls. A schematic diagram of this system is presented in Fig 2. Descriptions of experimental designs and other abbreviations used in the text are listed in Table 2.

2.2.3 Field management

Prior to 2012 the experimental field has been cultivated with potato without irrigation for 5 years. After the potato harvesting in 2011, the land was ploughed once and harrowed. Ridges were manually banked up with soil on the site from 20 March to 1 April 2012 before sowing. In order to smooth ridges before mulching, the clods on the ridges were broken into pieces with spades. Common plastic film and bio-degradable mulching were mulched on ridges with edges buried under in 3-5cm depth soil along base of ridges. Soil on SR was manually compacted with wooden boards from 2 to 4 April 2012. The furrows were leveled as planting belts. The

configurations of ridges and furrows were maintained and used in Alfalfa following growing seasons. The procedure of ridge mulching for CMR and BMR was repeated from 7 to 9 April 2013 after soil being completely thawed. SR remained without being destroyed.

According to local fertilizer application, a base fertilizer containing 150 kg N ha⁻¹, 41 kg P ha⁻¹ and 39 kg K ha⁻¹, was spread evenly over planting belts and then ploughed into soil in 20-25 cm depth before sowing in 2012. The sowing rate and fertility application rate were at the same levels based on planting areas on RFRWH and controls fields. Each plot of RFRWH had the same planting areas (furrow areas) and the same application rates. But the planting areas in the control fields (FP without alternative ridges and furrows) were higher than other plots in RFRWH. No irrigation and fertilization was applied after Alfalfa sowing. A local Alfalfa cultivar (Gannong No 3) was used as an indicator crop at 22.5 kg ha⁻¹. The cultivar, developed at Gansu Agricultural University, has a high forage yield and drought tolerance. Sowing was done on 10 April 2012. Four rows were sown in a 60 cm wide furrow with a 20 cm space between 2 rows and in a 2-3 cm depth. The planting areas were 18 m² (3 furrows × 10 m length × 0.6 m width) with 16 rows of Alfalfa for each RFRWH plot except for FP. FP areas were 36 m² (3.6 width × 10 m length) with 24 alfalfa rows. Weeds were controlled manually on 10 May, 15 June and 23 July 2012, and 4 May, 15 June and 19 July 2013, but not causing destruction of ridge soil crust. Alfalfa was harvested manually twice (19 August and 16 October) in 2012 and 3 times (11 July, 20 August and 27 October) in 2013.

2.4 Sampling and measurements

2.4.1 Rainfall and runoff

Rainfall was measured using an automatic weather station (WS-STD1, England) at the experimental station. The runoff depth of each ridge was determined by measuring volume of runoff in buckets and dividing this by the vertical ridge areas. The runoff volume in bucket was equal to the inner basal area of bucket multiplying

runoff depth. The buckets were emptied after measurement to ensure enough space for next runoff collection.

2.4.2. Soil moisture

During Alfalfa growing seasons, soil moisture was determined gravimetrically to a depth of 140 cm in 2012 and 140, 200 and 300 cm in 2013, with an increment of 20 cm, at 10 days intervals, including before sowing and after cutting. Apart from regular measurements, soil water content was also measured after each rainfall (>5 mm).

2.4.3. Soil temperature

A set of mercury-in-glass geothermometers with bent stems (Hongxing Thermal Instruments, Wuqiang County, Hebei Province, China) were placed at furrow bottoms and at ridge tops with every plot, at soil depths of 5, 10, 15, 20 and 25 cm. In both years, Soil temperature was recorded around at 8:00am, 2:00pm, and 6:00 pm daily at 5 days intervals between sowing and the last cutting. The mean daily soil temperature was calculated as the mean of the 3 daily recordings.

2.4.4. Forage yields

At initial flowering stage (19 August 2012 and 11 July, 20 August 2013) and stopping growing times (16 October 2012 and 27 October 2013), Alfalfa was harvested (cut near soil surface) manually twice in 2012 and 3 times in 2013. About 1 kg Alfalfa samples were dried in an oven at 105°C for 1 h and then at 75 °C for a minimum of 72 h to determine forage dry matter. Final Alfalfa forage yield was determined by 2 approaches: (1) forage yield (FY₁) was based on furrow areas; (2) forage yield (FY₂) was based on land areas of ridges and furrows.

Total actual evapotranspiration (ET, mm) for Alfalfa growing seasons and WUE (kg ha⁻¹mm⁻¹) of Alfalfa forage yield were calculated using following formula (Li & Gong, 2002b):

$$\text{CMR, BMR and SR: } ET = P + Re \times P \times \frac{1}{2} + (W_1 - W_2) \quad (1)$$

$$WUE = \frac{FY}{ET} \quad (2)$$

$$244 \quad \text{FP: } ET = P + (W_1 - W_2) \quad (3)$$

$$245 \quad WUE = \frac{F}{YET} \quad (4)$$

246 Where P is Alfalfa growing season precipitation (mm), Re (%) is monthly
 247 average runoff efficiency for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀,
 248 CMR₄₅ and CMR₆₀, h₁ (cm) is ridge width, h₂ (cm) is furrow width, W₁ (mm) and W₂
 249 (mm), are amount of soil water storage in 200 cm depth measured 1 d before sowing
 250 and after the last cutting based on mean value from furrows and ridges for CMR,
 251 BMR and SR, except for FP. Percolation and recharge from groundwater is negligible
 252 in this region (Fabeiro et al., 2001).

253 W₁ and W₂ are based amount of soil moisture stored.

$$254 \quad W = \theta \times BD \times H \times 10 \quad (5)$$

255 Where θ is soil water content (%), H is soil layer thickness (cm); BD the bulk
 256 density (g cm⁻³).

257 The effects of treatments were determined using compared means, one-way
 258 Duncan's ANOVA procedure.

259 **3 Results**

260 **3.1. Rainfall and monthly runoff efficiency**

261 Mean monthly precipitation in 2012 and 2013 are shown in Fig 3. The total
 262 precipitation was 414.4 mm in 2012 and 448.8 mm in 2013, while precipitation during
 263 Alfalfa growing season was 380.7 mm and 427.9 mm. In 2012, 91.9 % of rainfall fell
 264 from 10 April to 16 October during Alfalfa growing season, while in 2013, 95.3% of
 265 rainfall fell from 20 March to 27 October during Alfalfa growing season. Rainfall
 266 characteristics for 2012 and 2013 were reported in prior research (Wang et al., 2015).
 267 The results revealed that around 65-69% rainfall was less than 5 mm. This is too small
 268 to be utilized by crops, and the total amount of annual rainfall depends mainly on a
 269 few large storms with over 10 mm of rainfall. Monthly rainfall was 22.5, 49.1, 58.1,
 270 78.1, 93.8, and 68.5 and 16.3 mm, respectively, in April, May, June, July, August,

September and October 2012, while in 2013 it was 25.0, 68.9, 36.1, 139.3, 85.0, 63.7 and 18.6 mm.

Average monthly runoff efficiency (Table 3) was calculated by dividing monthly runoff by the corresponding total volume of rainfall. Monthly average runoff efficiencies for SR were 0% in April in both years because of low rainfall (22.5 mm in 2012 and 25.0 mm in 2013). And monthly average runoff efficiencies of SR were low, ranging from 4% to 19% in May, June, and October 2012, and ranging from 5% to 14% in June, September, and October 2013 because of low rainfall. Monthly average runoff efficiency for SR was the highest, ranging from 43% to 54% in September 2012, and from 22% to 29% in August 2013. Monthly average runoff efficiencies for BMR and CMR were relatively low in April and October in accordance with low rainfall in both years, and were high from May to August with high rainfall. In 2012, average monthly runoff efficiencies for SR₃₀, SR₄₅ and SR₆₀ (Subscript 30, 45 and 60 refer to ridge widths in cm) were 19%, 22% and 23%, respectively, while in 2013 these were 12%, 13% and 15%. However average monthly runoff efficiencies were high for BMR and CMR. The mean for BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ was 70%, 77%, 81%, 74%, 79% and 85%, respectively, in 2012, while was 59%, 65%, 73%, 66%, 65% and 73% in 2013. The results also indicated that runoff efficiency increased with increasing ridge width. In 2012, average monthly runoff efficiencies for SR (mean of SR₃₀, SR₄₅ and SR₆₀), BMR (mean of BMR₃₀, BMR₄₅ and BMR₆₀) and CMR (mean of CMR₃₀, CMR₄₅ and CMR₆₀) were 21%, 76% and 79% respectively, while in 2013 these were 14%, 66% and 68%. Average monthly runoff efficiencies were consistently higher in 2012 than in 2013 for all treatments. This was attributed to more rainfall events of greater intensity in 2012 than in 2013.

3.2. Soil temperature

Topsoil (in 0-25 cm) temperatures at furrow bottoms and ridge tops for various treatments during 2012 and 2013 Alfalfa growing seasons are shown in Fig 4. Topsoil

temperatures increased with increasing air temperature at seedling stage, and decreased with rainfall and decreasing air temperature in early autumn. Topsoil temperatures at furrow bottoms and ridge tops reached high levels in mid June 2012 and in early June 2013, and dropped in early September both years. The topsoil temperature during Alfalfa growing season, ranging from 9.7°C to 23.3°C at furrow bottoms and from 11.0°C to 28.4°C at ridge tops in 2012, was lower than that ranging from 11.0 °C to 25.3 °C at furrow bottoms and from 11.3 °C to 29.7 °C at ridge tops in 2013. Differences of topsoil temperature between different treatments are small after big storms, especially at furrow bottoms. No distinct differences of soil temperature were found at furrow bottoms between different treatments in most Alfalfa growing seasons, but distinct differences were found at ridge tops. The effect of RFRWH on soil temperature at ridge tops was larger during early Alfalfa growth stages and after cutting, because of large ridge areas exposed to solar radiation. In 2012, average soil temperatures at furrow bottoms during Alfalfa growing season were 16.7, 16.0, 16.3, 16.2, 16.4, 16.5, 16.8, 16.6, 16.4 and 16.6°C for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, while in 2013 these were 16.4, 16.3, 15.9, 16.3, 16.7, 17.3, 16.7, 16.6, 16.4 and 16.8. In 2012, average soil temperatures at ridge tops during Alfalfa growing season were 16.7, 17.5, 17.9, 18.2, 20.3, 21.1, 21.2, 21.5, 22.0 and 22.3°C for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅, CMR₆₀, respectively, while in 2013 these were 16.7, 17.6, 18.3, 18.3, 20.3, 20.9, 21.1, 20.7, 21.4 and 21.4°C. Under the same mulching material, average soil temperatures at ridges tops increased with increasing ridge width, but no distinct differences were found between 3 ridge widths. In 2012, average soil temperatures at ridges tops during Alfalfa growing seasons were 16.7, 17.9, 20.9 and 21.9°C for FP, SR, BMR and CMR, respectively, while in 2013 these were 16.7, 18.1, 20.8 and 21.2°C. The topsoil temperature at ridges tops in CMR was

higher than that in BMR, which was higher than that in SR, which was higher than that in FP.

3.3 Soil water storage

Soil water storage is defined as the total amount of water stored in soil within crop root zone. Normal variations in rainfall, evapotranspiration, soil texture, root depth, mulching and ridge-furrow configuration led to obvious differences in soil water storage (0-140 cm) during Alfalfa growing seasons for all treatments in both years (Fig 5). In this trial, in 2012 soil was sampled to 140 cm depth and in 2013 to 140, 200 and 300 cm. In order to compare the soil water storage over 2 years, the same soil depth (140 cm) was selected for both years. Soil water storage changed with rainfall patterns and Alfalfa growing seasons. The soil water storage from June to August reached the lowest level in 2012 because of high evapotranspiration and Alfalfa growth rate, but only average rainfall. But in 2013 soil water storage fluctuated a little during Alfalfa growing season for all treatments because of high rainfall (139.3 mm) in July. The high rainfall in July 2013 did not distinctly increase soil water storage because of high air temperature, topsoil temperature, wind speed and evapotranspiration in this region. Distinct differences in soil water storage at furrow bottoms profile were found between FP, SR, BMR and CMR, except in early Alfalfa growing season in 2012. Soil water storage was in order of CMR > BMR > SR > FP. It was hard for common plastic film to degrade under natural conditions, and it was only broken by wind, weed growth and animal destruction. Bio-degradable mulch film, however, was also eroded by microorganisms, beginning to degrade after 75 days mulching. The soil crust on SR deepened after rainfalls. This was attributed to runoff efficiency in order of CMR > BMR > SR. Local rainfall is usually less than 20 mm, which was not sufficient to induce runoff in FP. Soil water storage increased with increasing ridge width. For example in 2012 average soil water storage during Alfalfa growing season was 247, 260, 266, 273, 277, 286, 293, 284, 290 and 303 mm for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀,

respectively, while these was 183, 196, 200, 204, 203, 210, 224, 211, 219 and 229 mm.

3.4 Forage yield

Alfalfa grew slowly in both RFRWH and FP from April to June 2012. But Alfalfa grew normally from July to September 2012 and in the second year after sowing. There were 2 methods to calculate Alfalfa forage yields in Table 5. FY₁ reflected single plant productivity and FY₂ reflected land productivity. FY₁ was always higher than FY₂. FY₁ for RFRWH was significantly higher than those for FP in both years. The following discussion on forage yields was based on FY₂. In 2012 the contribution rates of the first cut to annual total forage yields were 54%, 50%, 52%, 52%, 55%, 58%, 58%, 55%, 57% and 58% for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, while in 2013 these were 33%, 42%, 42%, 44%, 42%, 44%, 44%, 42%, 44% and 43%. In 2012 the contribution rates of the second cut to annual total forage yields were 46%, 50%, 48%, 48%, 45%, 42%, 42%, 45%, 43% and 42% for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, while in 2013 these were 45%, 40%, 39%, 39%, 38%, 36%, 36%, 37%, 36% and 37%. In 2013 the contribution rates of the third cut to annual total forage yields were 22%, 18%, 18%, 17%, 20%, 20%, 19%, 21%, 20% and 20% for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively.

Post dormant emergency occurred 5-7 days ahead, and young growth was seen to be more rapid and vigorous for RFRWH plots than for FP plots. Forage yields for differences treatments also differed between cuts. Regarding to annual total forage yields, under SR planting, in 2012 forage yield was significantly higher in SR₃₀ than that in SR₄₅, which was significantly higher than that in SR₆₀. In 2013 forage yield was significantly higher in SR₃₀ than that in SR₆₀, and no significant difference was found between SR₄₅ and SR₃₀, and SR₄₅ and SR₆₀. Under BMR planting, in 2012 forage yield was significantly higher in BMR₄₅ than that in BMR₃₀ and BMR₆₀, and no

significant difference was found between BMR₃₀ and BMR₆₀. In 2013 forage yield was significantly higher in BMR₃₀ than that in BMR₄₅, which was significantly higher than that in BMR₆₀. The differences of forage yields between different treatments under CMR were similar to those under BMR in both years. Under the same mulching material in 2012, forage yields for 45 cm ridge width (BMR₄₅ and CMR₄₅) were highest under BMR and CMR planting, while 30 cm ridge width (SR₃₀) were highest under SR planting. In 2013, forage yields of 30 cm ridge width (BMR₄₅, CMR₄₅ and SR₃₀) were highest under SR, BMR and CMR planting. In 2012, average forage yields for CMR (mean of CMR₃₀, CMR₄₅ and CMR₆₀) were significantly higher than that for FP, which was significantly higher than that for SR (mean of SR₃₀, SR₄₅ and SR₆₀), and no significant differences were found between BMR (mean of BMR₃₀, BMR₄₅ and BMR₆₀) and CMR, and BMR and FP. In 2013 forage yields for CMR and BMR treatments were significantly higher than that for FP, which were significantly higher than that for SR, and no significant differences were found between BMR and CMR.

Single plant production (FY₁) was promoted for SR, BMR and CMR, but land production (FY₂) only increased in BMR and CMR. In 2012, average forage yield decreased by 8%, 18% and 26% for SR₃₀, SR₄₅ and SR₆₀, respectively, while in 2013 they decreased by 1%, 6% and 13% compared with FP. In 2012, average forage yield increased by 3%, 10%, 2%, 9%, 16% and 5% for BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, while in 2013 they increased by 39%, 27%, 18%, 43%, 31% and 21%. Average forage yield decreased by 17% in 2012 and by 7% in 2013 for SR. Average forage yield increased by 5% in 2012 and by 28% in 2013 for BMR, while it increased by 10% and 32% for CMR.

3.5 Water use efficiency

In 2012, WUE for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ was significantly higher than that for FP, and no significant differences were found between SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ (Fig 6). In 2013, under SR treatment, WUE for SR₆₀ was significantly higher

than that for SR₃₀, and no significant differences were found between SR₄₅ and SR₆₀, and between SR₄₅ and SR₃₀. Under BMR treatment, WUE for BMR₃₀ was significantly higher than that for BMR₆₀, and no significant difference was found between BMR₄₅ and BMR₃₀, and between BMR₄₅ and BMR₆₀. The differences of WUE between treatments under CMR were similar to those under BMR. On average, WUE for SR, BMR and CMR was significantly higher than that for FP, and no significant differences were found between SR, BMR and CMR in both years. In 2012, the increases of WUE for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ were 5.23, 5.74, 5.69, 4.97, 6.31, 6.05, 5.09, 6.60 and 5.43 kg ha⁻¹ mm⁻¹, respectively, while in 2013 these were 12.04, 14.43, 15.25, 16.38, 15.07, 13.15, 15.99, 15.29 and 13.72 kg ha⁻¹mm⁻¹ compared with FP. In 2012, average WUE for SR, BMR and CMR was 1.57, 1.60 and 1.59 times greater than for FP respectively, while in 2013 average WUE was 1.76, 1.81 and 1.82 times greater.

3.6 Optimum ridge: furrow ratio determination

It is unnecessary to calculate optimum ridge-furrow ratio for SR treatment because its forage yield (FY₂) was significantly lower than that for FP in both years.. For this reason, SR treatment was apparently not useful in this region when precipitation during Alfalfa growing season exceeds 380.7 mm (2012) and 427.6 mm (2013). To determine optimum ridge-furrow ratio for BMR and CMR planting, all the data was analyzed regressively by quadratic equation and it was assumed that FP treatment without ridges corresponded to a ridge width of 0 cm [Forage yield (y), and the ridge width (x) for BMR₃₀ (or BMR₃₀), BMR₄₅ (CMR₄₅), BMR₆₀ (CMR₆₀) and FP are 30, 45, 60 and 0 cm respectively]. In 2012, the regression equation for 2012 forage yield is $y = -0.4051x^2 + 29.395x + 4089.6$ ($R^2 = 0.7588$) for CMR and $y = -0.2096x^2 + 15.299x + 4091.9$ ($R^2 = 0.5172$) for BMR. For 2013 forage yield, the regression equation is $y = -2.7508x^2 + 190.48x + 8500.8$ ($R^2 = 0.9432$) and $y = -2.4559x^2 + 169.73x + 8493.6$ ($R^2 = 0.9441$); (see Fig 7). The regression equation indicated that a ridge width of 36 cm gave the highest yield for CMR and BMR in

2012 and of 35 cm in 2013. Thus furrow width was 60 cm and ridge width was 35-36 cm for CMR and BMR were optimum, and resulted in the highest Alfalfa forage yield for these 2 years.

4 Discussion

Rainfall is unpredictable in semi-arid regions, where maximum utilization of rainfall, especially light rainfall, is the key to successful agricultural production. Global warming is apparently leading to erratic precipitation patterns and high temperatures. There are obvious advantages in employing RFRWH techniques. CMR and BMR produced a high rate, but SR produced a low rate, of runoff efficiency. The reason for this was that all the rainfall for CMR and BMR was lost by evaporation and floor interception before runoff could be collected into water buckets. Also rainfall for SR was lost by permeation, and runoff occurred for SR when rainfall intensity was higher than infiltration rate (Li & Gong, 2002; David & Liu, 2014), and with other high intensity rainfall events (Li et al., 2004). Compared with CMR, BMR produced a relatively low rate of runoff efficiency. The reason for this was that bio-degradable mulching film was more quickly and easily broken than common plastic film. This result indicated the runoff efficiency of ridges increased with increasing ridge width, because narrower ridges width resulted more precipitation be deflected to runoff. This result confirmed that BMR and CMR had high rainwater harvesting effects on Alfalfa growth and production. SR, however, had low rainwater harvesting effects, except with high rainfall. Choice of optimum ridge width and suitable ridge-mulching material depends largely on local rainfall, soil type and depth, land topography and plant species. Ridge-mulching material should be simple and inexpensive, and bio-degrade under natural conditions. In this region, because of high evaporation, when rainfall is less than 5 mm, it cannot be absorbed by soil and therefore by plant (Li, et al., 1999). Furrows received rainfall directly, as well as runoff from ridges. Coupling rainfall with runoff, an ineffective rainfall can be changed into an effective rainfall event for plant uptake. Rainfall of more than 5 mm is considered to be

effective, but for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, threshold rainfall was 4.3, 4.3, 4.2, 3.0, 2.9, 2.8, 2.9, 2.9 and 2.8 mm respectively, over 2 years, and average threshold rainfall for SR, BMR and CMR were 4.3, 2.9 and 2.9 mm respectively, over 2 years. (Li et al., 2007) revealed that a rainfall of less than 4-5.3 mm was not able to generate an effective runoff for SR, while a rainfall of more than 1 mm could generate an effective runoff for CMR.

Mulched ridges served to be rainwater harvesting zones, while non-mulched furrows served to be planting zones. Plant height, density, and coverage did not distinctly affect topsoil temperature at furrow bottoms for all treatments. But mulching materials of ridges affect distinctly topsoil temperature at ridge tops. Common plastic film and bio-degradable mulch film reduced latent heat flux, and heat exchange between soil and ambient air (Zhao et al., 2014), and CMR and BMR increased topsoil temperatures at ridge tops compared to FP. Mulched ridge reduced wind speed in furrows and increased ridge soil temperature, and soil heat was transmitted from ridge soil to furrow soil (Zhang et al., 2008). Distinct differences were not found between furrow topsoil temperatures between different treatments in this experiment. Soil crust on ridges reduced heat exchange between soil and ambient air, but this reduction in heat exchange was less than with common plastic film and bio-degradable mulch film. Several investigators have reported that the soil thermal regime under common plastic film was higher than that under bared lands (Zhou et al; Sarkar et al., 2007). Compared with FP, the increase in growing seasons average topsoil temperature on ridge tops was 1.0, 1.5, 1.7, 3.8, 4.4, 4.6, 4.5, 5.2 and 5.3 °C in SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ respectively, over 2 years.

Furrow width was the same for all treatments. Rainwater coupled with runoff can logically increase soil water content in furrows. Wider ridges harvested more rainwater in furrows. High soil water content in furrows stimulated root development, and plant roots extended into ridge soil. Root dry matter, length, surface area, and

volume in furrow sides were higher than in mid furrow, which indicated that oats grown in furrow sides are likely to produce higher forage and grain yields than it grown in mid furrow (Li et al., 2014). Soil water depletion is related to spatial distribution of crop roots (Wang et al., 2010). Compared with FP, increase of average soil water storage during Alfalfa growing seasons 13, 18, 23, 25, 33, 44, 33 , 40 and 51 mm for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ respectively, over 2 years.

In general, single plant productivity was significant higher for SR, BMR and CMR than for FP, because this rainfall and organic matter was concentrated in furrows. Compared with FP, CMR generated significantly high land productivity in both years, while for BMR, and in 2012 land productivity was similar to that for FP and in 2013 a significantly high. Land productivity for SR was significantly lower in both years. We can conclude that ridges, mulched with bio-degradable mulching film or common plastic film, improved runoff, infiltration depth of soil water, and soil water retention of rainwater and runoff into furrows, and reduced soil evaporation and wind speed. Deep infiltration of soil water reduces losses of evaporation in furrows (Ramakrishna et al., 2006; Ghosh et al., 2006). Monthly runoff efficiency of BMR and CMR was high, especially from May to September. Forage yield trends corresponded well to high runoff efficiency and soil moisture in RFRWH system, which increased forage yield by 2-10% in 2012 and 18-39% in 2013 for BMR compared with FP, while forage yield increase was 5-16% in 2012 and 21-43% in 2013 for CMR. Bio-degradable mulching film was beginning to degrade after 75 days in mid-June, but rainfall is usually low before June, so it performed a similar useful function as common plastic film for early crop growth (Moreno & Moreno, 2008). Although Bio-degradable mulching film degraded earlier than common plastic film, the trial indicated that bio-degradable mulching film had similar benefits on soil water retention, soil temperature, and forage yield as common plastic film in both years. The monthly runoff efficiency for SR was low and the highest for each year being 48% in

September 2012 and 25% in August 2013. Runoff in SR was generated by a few larger high intensity storms. Ridges generated runoff and improved soil water storage, but reduced planting area. This created a negative effect on forage yield, especially in SR planting. Planting area for FP was twice that for SR₄₅, BMR₄₅ and CMR₄₅. Reduced planting area and low runoff efficiencies in SR decreased forage yield by 8-26% in 2012 and by 1-13% in 2013.

One of advantages of RFRWH is that rainfall coupled with runoff in furrows increased availability of soil moisture to plant roots. In 2012, rainfall coupled with runoff received during Alfalfa growing seasons for FP, SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ was 427.3, 426.0, 439.1, 463.4, 485.6, 569.2, 623.5, 505.6, 586.6 and 669.1mm, respectively, while in 2013 these were 459.2, 458.4, 482.6, 511.0, 560.5, 641.1, 739.1, 586.5, 654.0 and 741.6 mm. It can clearly be seen that rainwater received in BMR and CMR was distinctively more than that harvested in SR, which was more than that harvested in FP, and increased with increasing ridge width. This was probably because BMR and CMR reduced soil evaporation on ridges and augmented infiltration of rainwater into soil (Ramakrishna et al., 2006; Ghosh et al., 2006; Hu et al., 2014). Compared with FP, for the corresponding rainfall, the increases of WUE for maize at the rainfalls of 230, 340 and 440 mm under RFRWH planting were 77%, 43% and 10%, respectively (Ren et al., 2008). RFRWH is a helpful technique in areas with scarce water resources, but when rainfall is high, the benefit from WUE under RFRWH planting declines or disappears. In this trial, WUE for FP, SR, BMR and CMR was 16.33, 23.81, 24.43 and 24.35 kg ha⁻¹mm⁻¹, respectively, over 2 years. Boers et al (1986) reported that RFRWH would be suitable for desert regions with about 250 mm annual rainfall.

There is a tradeoff between ridge width reducing annual total forage yields, and runoff from ridge increasing soil water content, single plant yield and WUE. Optimum ridge width varied with the amount of rainfall, soil types, plant species, and cultivation practices. Prior research (Wang et al., 2015) found that optimum ridge

width was 32-38 cm for CMR and 30-34 cm for BMR for oats in this region. This experiment indicated that optimum ridge width was 35-36 cm for CMR and BMR for Alfalfa in this region. This was a preliminary optimization because other criteria were not taken into consideration when optimizing in the study: amount and intensity of rainfall, slope, crop type, economics, soil characteristics, etc. Future study is needed to investigate the optimum ridge-furrow ratio and suitable ridge-mulching material for achieving the best environmental and economic benefit under different climatic conditions, soil types and plant species using bio-degradable mulching materials such as grass, hay, wood chips, wood fibers, straw in semi-arid areas of Northwest China.

5 Conclusions

Average monthly runoff efficiency (expressed as a ratio of runoff to rainfall received during the same period) was 16%, 18%, 19%, 65%, 71%, 77%, 70%, 72% and 79% for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, over 2 years. For the same treatments, threshold rainfall was 4.3, 4.3, 4.2, 3.0, 2.9, 2.8, 2.9, 2.9, and 2.8 mm, respectively. In Alfalfa trials, ridge mulching materials and ridge widths had distinct effects on topsoil temperature at ridge tops, but not at furrow bottoms. The soil water storage in 140 cm depth at furrow bottoms profile increased with increasing ridge width and in the order of CMR $\approx$ BMR > SR > FP. Average forage yield decreased by 4%, 12% and 20% for SR₃₀, SR₄₅ and SR₆₀, and increased by 21%, 18%, 10%, 26%, 23% and 13% for BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀, respectively, over 2 years. Forage yields decreased with increasing ridge width. Compared with FP, the increases of WUE for SR₃₀, SR₄₅, SR₆₀, BMR₃₀, BMR₄₅, BMR₆₀, CMR₃₀, CMR₄₅ and CMR₆₀ were 8.64, 10.08, 10.47, 10.67, 10.69, 9.60, 10.54, 10.94 and 9.57 kg ha⁻¹mm⁻¹, respectively, over 2 years. Optimum ridge width was 35-36 cm for CMR and BMR for Alfalfa production in the RFRWH system with 60 cm furrow width in semi-arid areas of Northwest China.

Acknowledgments

This research was supported by the Chinese National Science Foundation (41161090) and (41461062).

References

Al-Rumikhani, Y.A., 2002. Effect of crop sequence, soil sample location and depth on soil water holding capacity under center pivot irrigation. *Agric. Water Manage.* 55(2), 93–104.

Boers, T.M., Zondervan, K., Ben-Asher, J., 1986. Micro-catchment-water-harvesting (MCWH) for arid zone development. *Agric. Water Manage.* 12(1-2), 21-39.

David, J. S., Liu, J., 2014. Optimizing rainwater harvesting systems for the dual purposes of water supply and runoff capture. *Journal of Cleaner Production*, 75, 174-194.

Deng, X.P., Shan, L., Zhang, H.P., Turner, Neil C., 2006. Improving agricultural water use efficiency in arid and semiarid areas of China. *Agric. Water Manage.* 80(1-3), 23-40.

Fabeiro, C., Martín-de-Santa-Olalla, F., de-Juan.J.A., 2001. Yield and size of deficit irrigated potatoes. *Agric. Water Manage.* 48(3), 255-266.

Ghosh, P.K., Dayal, D., Bandyopadhyay, K.K., Mohanty, M., 2006. Evaluation of straw and polythene mulch for enhancing productivity of irrigated summer groundnut. *Field Crop Res.* 99 (2-3), 76-86.

Gupta, G.N., 1995. Rainwater management for tree planting in the India desert. *J. Arid Environ.* 31(2), 219-235.

Hu, Q., Pan, F. f., Pan, X.B., Zhang, D., Yang, N., Pan, Z. H., Zhao, P. Y., Tuo, D.B., 2014. Effects of a ridge-furrow micro-field rainwater-harvesting system on potato yield in a semi-arid region. *Field Crops Res.* 166, 92–101.

Janette W. & Tim, H., 2006. Rainwater harvesting for domestic use. Digigrafi, Wageningen, The Netherlands.

Li, F.C., Ren, X., Wang, Q., Zhang, E.H., Huo, H.L., Wang, H.L., 2013. Effects of rainwater harvesting with ridges and furrows on root distribution of oat in semi-arid

605 areas. Chinese Journal of Ecology. 32(11), 2966-2972. (in Chinese)

606 Li, F.M., Guo, A.H., Wei, H., 1999. Effects of clear film mulch on yield of spring
607 wheat. Field Crop Res. 63(1), 293-304.

608 Li, X.L., Su, D.R., Yuan, Q.H., 2007. Ridge-furrow planting of alfalfa (*Medicago*
609 *sativa* L.) for improved rainwater harvest in rainfed semiarid areas in Northwest
610 China. Soil Till Res. 93(4), 117-125.

611 Li, X.Y., Gong, J.D., 2002a. Compacted catchment with local earth materials for
612 rainwater harvesting in the semiarid region of China. J. Hydrol. 257(1-4), 134-144.

613 Li, X.Y., Gong, J.D., 2002b. Effect of different ridge: furrow ratios and supplement
614 irrigation on crop production in ridge and furrow rainfall harvesting system with
615 mulches. Agric. Water Manage. 54(3), 243-254.

616 Li, X.Y., Gong, J.D., Gao, Q.Z., Wei, X.H., 2000a. Rainfall interception loss by
617 pebble mulch in the semiarid region of China. J. Hydrol. 228(3-4), 165-173.

618 Li, X.Y., Gong, J.D., Wei, X.H., 2000b. In-situ rainwater harvesting and gravel mulch
619 combination for corn production in the dry semi-arid region of China. J. Arid Environ.
620 46(4), 371-382.

621 Li, X.Y., Xie, Z.K., Yan, X.K., 2004. Runoff characteristics of artificial catchment
622 materials for rainwater harvesting in the semiarid regions of China. Agric. Water
623 Manage. 65(3), 211-224.

624 Liu, C.A., Jin, S.L., Zhou, L.M., Y, J., Li, F.M., Xiong, Y.C., Li, X.G., 2009. Effects
625 of plastic film mulch and tillage on maize productivity and soil parameters. Eur. J
626 Agron. 31(4), 241-249.

627 Liu, X.E., Li, X. G., Hai, L., Wang, Y. P., Fu, T.T., Neil, C. T., Li, F. M., 2014.
628 Film-mulched ridge–furrow management increases maize productivity and sustains
629 soil organic carbon in a dryland cropping system. Soil Sci. Soc. Am. J. 78,
630 1434-1441.

631 Moreno, M.M., Moreno, A., 2008. Effect of different biodegradable and polyethylene
632 mulches on soil properties and production in a tomato crop. Sci. Hortic-Amsterdam.

633 116(3), 256-263.

634 Qin, D.H., Ding, Y.H., Wang, S.W., Wang, S.M., Lin, Dong G.R., Liu, E.D., She,
635 C.Z., Sun, Z. X., Wang, H.N., Wu, S.R., G. H., 2002. Ecological and environmental
636 change in West China and its response strategy. *Adv. Earth Sci.* 17(3), 314-319.

637 Ramakrishna, A., Tam, H.M., Wani, S.P., Long, T.D., 2006. Effect of mulch on soil
638 temperature, moisture, weed infestation and yield of groundnut in northern Vietnam.
639 *Field Crop Res.* 95(2-3), 115-125.

640 Ren, X.L., Jia, Z.K., Chen, X.L., 2008. Effects of a rainwater-harvesting furrow/ridge
641 system on spring corn productivity under simulated rainfalls. *Acta Ecologica Sinica.*
642 28(3), 1006–1015. (in Chinese)

643 Sarkar, S., Paramanick, M., Goswami, S.B., 2007. Soil temperature, water use and
644 yield of yellow sarson (*Brassica napus* L. var. *glauca*) in relation to tillage intensity
645 and mulch management under rainfed lowland ecosystem in eastern India. *Soil Till*
646 *Res.* 93(1), 94-101.

647 Shan, L., and Chen, G.L., 1993. The theories and practices of dry-land agriculture in
648 Loess Plateau. Scientific Publisher, Beijing, pp. 222-229. (in Chinese).

649 Wan, S.M., Huang, Q.H., Hu, S.L., Wang, L.C., Hu, J.H., 2004. Study on soil water
650 condition and yield of alfalfa cultivars in Weibei plateau. *Agric. Res. Arid Areas* 22
651 (3), 14–18 (in Chinese).

652 Wang, Q., Ren, X., Song, X.Y., Hu, G.R., Zhang, E.H., Wang, H.L., Maureen., 2015.
653 The optimum ridge–furrow ratio and suitable ridge-covering material in rainwater
654 harvesting for oats production in semiarid regions of China. *Field Crop Res.* 172,
655 106-118.

656 Wang, Q, Zhang, E.H., Li, F.M., Li, F.R., 2008. Runoff efficiency and the technique
657 of micro-water harvesting with ridges and furrows for potato production in semiarid
658 areas. *Water Resour Manage.* 22(10), 1431-1443.

659 Wang, Y.Q., Shao, M.A., Liu, Z.P., 2010. Large scale spatial variability of dried soil
660 layers and related factors across the entire Loess Plateau of China.

661 Geoderma.159(1-2), 99-108.

662 Zhang, S., Carmi, G., Berliner, P., 2013. Efficiency of rainwater harvesting of
 663 microcatchments and the role of their design. J. Arid Environ., 95, 22-29.

664 Zhang, Z.C., Zhang, S.F., Yang, J.C., 2008. Yield, grain quality and water use
 665 efficiency of rice under non-flooded mulching cultivation. Field Crops Res. 108(1),
 666 71–81.

667 Zhao, C.Y., Feng, Z.D., Chen, G.D., 2004. Soil water balance simulation of alfalfa
 668 (*Medicago sativa* L.) in the semiarid Chinese loess plateau. Agric. Water Manage.
 669 69(2), 101–114.

670 Zhao, H, Wang, R.H., Ma, B.L., Xiong, Y.C., Qiang, S.C., Wang, C.L., Liu, C.A., Li,
 671 F.M., 2014. Ridge-furrow with full plastic film mulching improves water use
 672 efficiency and tuber yields of potato in a semiarid rainfed ecosystem. Field Crop Res.
 673 161, 137-148.

674 Zhao, H.L., Zhao, X.Y., Zhang, T.H., Zhou, R.L., 2002. Boundary line on
 675 agro-pasture zigzag zone in north China and its problems on eco-environment. Adv.
 676 Earth Sci. 17(5), 739–747.

677 Zhao, Q.Y., Zhang, W., Wang, S.G., Liu, X.W., 2005. Change of extreme
 678 precipitation events in arid and semi-arid regions in the east of northwest China. J.
 679 Desert Res. 25(6), 904-909.

680 Zhou, L.M., Li, F.M., Jin, S.L., Song, Y.J., 2009. How two ridges and the furrow
 681 mulched with plastic film affect soil water, soil temperature and yield of maize on the
 682 semiarid Loess Plateau of China. Field Crop Res. 113(1), 41-47.

Fig 1 Schematic diagram showing runoff efficiency in ridge-furrow rainwater harvesting system

Fig 2 Schematic diagram for Alfalfa production in ridge-furrow rainwater harvesting system.

Fig 3 Mean monthly precipitation at the experiment site in 2012 and 2013

Fig 4 Soil temperature at furrow bottoms and at ridge tops in 0-25 cm soil depth in various treatments. FP was the flat planting, and SR, BMR and CMR were ridges with manually compacted soil, covered with bio-degradable mulch film and with common plastic film, respectively. The ridge widths of SR₃₀, SR₄₅ and SR₆₀ (BMR₃₀, BMR₄₅ and BMR₆₀ or CMR₃₀, CMR₄₅ and CMR₆₀) were 30, 45 and 60 cm, respectively, with 60 cm furrow width for all treatments.

Fig 5 Soil water storage furrow bottoms in 0-140 cm soil depth in various treatments.

FP was the flat planting, and SR, BMR and CMR were ridges with manually compacted soil, covered with bio-degradable mulch film and with common plastic film, respectively. The ridge widths of SR₃₀, SR₄₅ and SR₆₀ (BMR₃₀, BMR₄₅ and BMR₆₀ or CMR₃₀, CMR₄₅ and CMR₆₀) were 30, 45 and 60 cm, respectively, with 60 cm furrow width for all treatments.

Fig 6 Water use efficiency (kg ha⁻¹ mm⁻¹) of Alfalfa under ridge-furrow rainwater harvesting.

FP was the flat planting, and SR, BMR and CMR were ridges with manually compacted soil, covered with bio-degradable mulch film and with common plastic film, respectively. The ridge widths of SR₃₀, SR₄₅ and SR₆₀ (BMR₃₀, BMR₄₅ and BMR₆₀ or CMR₃₀, CMR₄₅ and CMR₆₀) were 30, 45 and 60 cm, respectively, with 60 cm furrow width for all treatments. The means (columns) labeled with the same letters within each group are not significantly different at the 5% level (Duncan's One-Way ANOVA).

Fig 7 Alfalfa forage yield as a function of ridge width for CMR and BMR in 2012 and 2013
 BMR and CMR were ridges covered with biodegradable mulch film and with common plastic film, respectively.

Table 1 Physical and chemical properties of soil profiles in the experimental plots

Depth	Bulk	Field	Total	Total	Total	Organic	Available	Olsen	Available	pH
cm	density	capacity	N	P	K	matter	N	P	K	
	g cm ⁻³	%	g kg ⁻¹	g kg ⁻¹	g kg ⁻¹	%	mg kg ⁻¹	mg kg ⁻¹	mg kg ⁻¹	
0-40	1.38	25.6	0.84	1.24	23.10	11.07	51.1	14.12	201.4	7.8

Table 2 Experimental design for Alfalfa production in ridge-furrow rainwater harvesting system

Treatments	Furrow : ridge cm: cm	Area of ridge m ²	Area of plot m ²	Area of furrow m ²	Mulching material
FP	/	/	36	/	/
SR ₃₀	60: 30	12	30	18	
SR ₄₅	60: 45	18	36	18	Soil crust
SR ₆₀	60: 60	24	42	18	
BMR ₃₀	60: 30	12	30	18	Biodegradable mulch film
BMR ₄₅	60: 45	18	36	18	
BMR ₆₀	60: 60	24	42	18	
CMR ₃₀	60: 30	12	30	18	
CMR ₄₅	60: 45	18	36	18	Common plastic film
CMR ₆₀	60: 60	24	42	18	

Table 3 Monthly runoff efficiency (%) for ridges with manually compacted soil (SR), ridges covered with bio-degradable mulching film (BMR) and common plastic film (CMR) in 2012 and 2013.

Treatments	Apr	May	Jun	Jul	Aug	Sep	Oct	Mean
2012								
SR ₃₀	0	12	14	20	22	43	4	19
SR ₄₅	0	15	15	20	24	54	5	22
SR ₆₀	0	16	19	25	27	47	4	23
BMR ₃₀	59	59	74	77	82	77	59	70
BMR ₄₅	69	74	78	81	85	85	70	77
BMR ₆₀	71	81	81	85	89	87	75	81
CMR ₃₀	71	71	77	80	83	78	59	74
CMR ₄₅	74	79	81	80	84	85	69	79
CMR ₆₀	81	86	83	87	89	88	77	85
Mean								
SR	0	14	16	22	25	48	4	21
BMR	66	71	78	81	85	83	68	76
CMR	76	79	80	82	86	84	68	79
2013								
SR ₃₀	0	18	12	12	22	5	5	12
SR ₄₅	0	18	13	13	25	6	5	13
SR ₆₀	0	23	13	14	29	7	6	15
BMR ₃₀	44	76	41	75	73	54	52	59
BMR ₄₅	48	75	51	83	80	63	58	65
BMR ₆₀	51	82	66	91	85	68	67	73
CMR ₃₀	52	76	51	85	80	59	56	66
CMR ₄₅	49	75	44	81	81	64	64	65
CMR ₆₀	62	80	54	92	87	70	68	73
Mean								
SR	0	19	13	13	25	6	5	14
BMR	48	78	52	83	79	62	59	66
CMR	54	77	49	86	83	65	63	68

Subscript 30, 45 and 60 refer to ridge widths in cm.

Table 5 Alfalfa forage yield (kg ha⁻¹) in ridge-furrow rainwater harvesting system

Treatments	First cut		Second cut		Third cut		Annual total		Increase %
	FY ₁	FY ₂	FY ₁	FY ₂	FY ₁	FY ₂	FY ₁	FY ₂	
2012									
FP	2215h	2215d	1897f	1897bc	/	/	4112g	4112d	/
SR ₃₀	3187g	1912e	3136e	1882bc	/	/	6323f	3794e	-8
SR ₄₅	3490fg	1745ef	3255cde	1628e	/	/	6746ef	3373f	-18
SR ₆₀	3665ef	1571f	3395c	1455f	/	/	7060de	3026g	-26
BMR ₃₀	3885de	2331cd	3184de	1910bc	/	/	7069de	4241cd	3
BMR ₄₅	5213c	2606ab	3821b	1911bc	/	/	9034c	4517b	10
BMR ₆₀	5727ab	2454bc	4062a	1741d	/	/	9788ab	4195d	2
CMR ₃₀	4125d	2475bc	3329cd	1997ab	/	/	7454d	4472bc	9
CMR ₄₅	5449bc	2724a	4095a	2047a	/	/	9543b	4772a	16
CMR ₆₀	5867a	2514bc	4230a	1813cd	/	/	10098a	4328bcd	5
Mean									
TP	2215c	2215b	1897c	1897a	/	/	4112c	4112b	/
SR	3447b	1743c	3262b	1655b	/	/	6710b	3397c	-17
BMR	4942a	2464a	3689a	1854a	/	/	8630a	4318ab	5
CMR	5147a	2571a	3885a	1952a	/	/	9031a	4524a	10
2013									
FP	2822g	2822d	3784g	3784b	1835d	1834f	8440g	8440e	/
SR ₃₀	5836f	3502c	5565f	3339cd	2550c	1530g	13951f	8370e	-1
SR ₄₅	6712e	3356c	6228ef	3114de	2892c	1446g	15832e	7916ef	-6
SR ₆₀	7483d	3207c	6719de	2880f	2996c	1284g	17198d	7371f	-13
BMR ₃₀	8188c	4913a	7341cd	4405a	3966b	2380ab	19495c	11697a	39
BMR ₄₅	9415b	4708ab	7793bc	3897b	4249ab	2125bcd	21458b	10729bc	27
BMR ₆₀	10323a	4424b	8491ab	3639bc	4512a	1934ef	23327a	9997d	18
CMR ₃₀	8415c	5049a	7552c	4531a	4207ab	2524a	20174c	12104a	43
CMR ₄₅	9633ab	4816a	7895bc	3947b	4505a	2252abc	22032b	11016b	31
CMR ₆₀	10307a	4417b	8846a	3791b	4670a	2001cde	23822a	10209cd	21
Mean									
TP	2822c	2822c	3784c	3784a	1835c	1835b	8440d	8440b	/
SR	6677b	3355b	6171b	3111b	2813b	1420c	15660c	7886c	-7
BMR	9309a	4681a	7875a	3980a	4243a	2146a	21427b	10808a	28
CMR	9452a	4761a	8097a	4090a	4460a	2259a	22009a	11110a	32

Means within a column followed by the same letters are not significantly different at the 5% level (Duncan's One-Way ANOVA). FY₁ was forage yields based on furrow area. FY₂ was Alfalfa forage yields based on land areas of ridges and furrows. FP was the flat planting, and SR, BMR and CMR were ridges with manually compacted soil, covered with bio-degradable mulch film and with common plastic film, respectively. The ridge widths of SR₃₀, SR₄₅ and SR₆₀ (BMR₃₀, BMR₄₅ and BMR₆₀ or CMR₃₀, CMR₄₅ and CMR₆₀) were 30, 45 and 60 cm, respectively, with 60 cm furrow width for all treatments.