Journal of Soil Science and Plant Nutrition (2022) 22:2587–2602
https://doi.org/10.1007/s42729-022-00829-5

ORIGINAL PAPER

Effect of Co-application of Ridge-Furrow Rainwater Harvesting and Mulching on Fodder Yield, Quality, and Soil Desiccation in Alfalfa (*Medicago sativa*) Production

Erastus Mak-Mensah[1] · Dengkui Zhang[1] · Xujiao Zhou[1] · Xiaole Zhao[1] · Xiaoyun Wang[1] · Wucheng Zhao[1] · Qi Wang[1] · John K. Ahiakpa[2]

Received: 15 December 2021 / Accepted: 16 March 2022 / Published online: 29 March 2022

Abstract
Alfalfa (*Medicago sativa*) is a major crop grown in northwestern China, but severe water shortages due to low rainfall and soil erosion hinder the growth of the crop. An increase in water availability is essential for continuous alfalfa cultivation; however, only a few studies have assessed ridge-furrow rainwater harvesting effects on alfalfa yield and water use efficiency. To expand on these studies, we evaluated the effect of plastic film mulched ridge-furrow rainwater harvesting on fodder yield and quality. This study had ten treatments with three ridge-mulching materials and three ridge widths and flat planting (FP) as a control laid out in a randomized complete block design (RCBD) with three replications for 5 years. Compared to flat planting, ridges mulched with plastic film increased yield (33%) and water use efficiency (19.79%) by decreasing crop water consumption (2.35%) over the cultivation seasons of alfalfa. Ridge mulched with plastic film (PF_{60}) had the highest crude protein of 202 g kg^{-1}, while ridge mulched with bio-degradable film (BF) had the lowest mean acid detergent fiber content of 348 g kg^{-1}. Flat planting had the highest neutral detergent fiber of 505 g kg^{-1}, while BF treatment had the lowest mean neutral detergent fiber of 471 g kg^{-1}. Thus, severe soil desiccation was observed during alfalfa cultivation seasons. Nevertheless, PF_{60} had the lowest degree of soil water deficit. Our results indicate that co-application of ridge-furrow rainwater harvesting and mulching in alfalfa production over the 5 years increased fodder yield and quality by markedly reducing soil desiccation with a higher cost–benefit ratio. We, therefore, recommend co-application of ridge-furrow rainwater harvesting and mulching with 60-cm ridge width under semiarid conditions for improving yield and decreasing soil desiccation.

Keywords Biodegradable film · Compacted soil · Mulching · Plastic film · Soil desiccation index · Water use efficiency

1 Introduction

Alfalfa is one of the world's most versatile crops, grown in environments ranging from burning hot deserts to cool high mountain valleys (Li and Su 2017). Many farmers and cultures value its high productivity, flexible wide adaptation to different soil types and climatic zones, and life-sustaining nutritional characteristics (Das et al. 2021). This adaptability occurs as a result of some strategies that alfalfa develop to sustain its growth in a wide range of environments, such as modification of its leaf area ratio or increasing shoot to root ratio to allow the roots to capture more water during drought (Anower et al. 2017). Consequently, this depletes underground water and water storage reservoirs rapidly, and continuous alfalfa cultivation can culminate in extreme soil desiccation (Das et al. 2021).

Drought is one of the most crucial factors limiting the growth and production of most economic crops worldwide. Therefore, proper soil management practices can be adopted for growing alfalfa in sunken beds for the utilization of seepage water from raised beds (Mak-Mensah et al. 2021a). A simple land configuration through ridge and furrow system is a useful technique for proper land and water management to increase crop water productivity (Amarasingha et al. 2017). Modification in field topography through the construction of alternate ridges and furrows improves the physical environment, particularly the aeration status of the

✉ Qi Wang
wangqigsau@gmail.com

[1] College of Grassland Science, Gansu Agricultural University, Lanzhou, China

[2] Research Desk Consulting Limited, Accra, Ghana

soil, and creates conducive conditions for crop growth (Das et al. 2021). Water management practices like "ridge-furrow rainwater harvesting" (RFRH) tackle water scarcity in a better way in rain-fed alfalfa cultivation and has the potential to contribute to more sustainable water use efficiency (Mak-Mensah et al. 2021b).

One of the most effective techniques in soil and water loss is mulching (Liu et al. 2018a). Ridge mulching increases soil temperature and precipitation infiltration and decreases crop water consumption (Mo et al. 2016). Mulching typically with plastic film, crop straw, animal manure, gravel-sands, and rocks are applied to fields before, during, or shortly after sowing (Yang et al. 2020). However, widespread materials applied in RFRH for mulching are straw and plastic film (Li et al. 2017a). Plastic films decrease soil water evaporation and increase crop transpiration, thus promoting crop yield (Mak-Mensah et al. 2021a). Despite these benefits, residual plastic film deposits adversely affect soil structure and transport of nutrients and water (He et al. 2018a).

Prior investigations of ridge-furrow rainwater harvesting systems in northwestern China have evaluated effects of agronomic practices on yield and water use efficiency in alfalfa production (Fan et al. 2019; He et al. 2018b; Jia et al. 2018; Li et al. 2017b; Zhang et al. 2021). However, to date, no evaluation has been conducted in the region to assess effects of ridge-furrow rainwater harvesting system with mulching on fodder yield, quality, soil desiccation, and their economic benefits. Therefore, this study was undertaken to evaluate the effects of ridge-furrow rainwater harvesting system with mulching on alfalfa yield, fodder quality, soil desiccation, and their economic benefits in northwestern China over 5 years. We anticipated that costs from mulching material would be compensated by improved alfalfa yield and fodder quality under ridge-furrow rainwater harvesting system and mulching compared to flat planting.

2 Materials and Methods

2.1 Study Area

Field experiments were conducted from 2012 to 2016 at Dingxi Arid Meteorology and Ecological Environment Experimental Station, Institute of Arid Meteorology of China Meteorological Administration. The station is located 3 km southeast of Dingxi City in Gansu Province, Northwest of China (35°34′59″ N 104°37′00″E, with an elevation of 1971 m a. s. l.). Dingxi is a semi-arid area with small farming villages sited in narrow valleys surrounded by mountains with a mean annual air temperature of 7.2 °C (Fig. 2a). During study seasons, the lowest and the highest annual mean temperatures were – 13.0 °C and 25.9 °C, respectively. Approximately 80% of rainfall, which contributed to annual mean rainfall of 408 mm, mainly occurred from May to September. Annual evapotranspiration (1500 mm) was measured by pan evaporation method according to Kader et al. (2017). Before sowing, loess-like loamy soil in experimental fields had gravimetric field water holding capacity of 25.6 mm and a mean bulk density of 1.38 Mg m^{-3}. The soil (upper 40 cm layer) had a permanent wilting point of 6.7%. The soil physicochemical properties were estimated (Table 1).

2.2 Experimental Design

In a randomized complete block design (RCBD), there were ten treatments of three ridge-mulching materials with three ridge widths and flat planting (FP) as control with three replications each. Alfalfa was spaced 20 cm apart in experimental plots, which were 3 m wide and 10 m long. The ridge was 20 cm in height and sloped at an angle of 40° (Fig. 1). Manually compacted soil (CS), biodegradable film (BF), and plastic film (PF) as ridge mulching materials with three ridge widths (30, 45, and 60 cm) were studied. The ridges were covered with plastic and biodegradable films with edges buried 3–5 cm in the soil along the bases of the ridges. During ridge banking, manually compacted soil was created by hand, and after a few rain events, it became crusted. The plastic and biodegradable films (composed of starch) were 0.008 mm thick and were obtained from Shijiazhuang Yongsheng Plastic Plant Co. Ltd (China) and BASF Co. Ltd, (Germany), respectively.

2.3 Field Management

After collecting litter and debris, plots on the fields were prepared and established in 2012. About 20–30-cm-thick surface layer of highly fertile soil was excavated and stacked. Using a slope meter and a tape measure, plots were manually constructed by molding soil surface into furrows and ridges at 40° slope to acceptable sizes (3.0–4.2 m wide and 10 m long, with 4 ridges and 3 furrows, except for controls) along breadths of plots. After plots were established, piles of dug-up soils were then spread uniformly over plots using a spade. The furrows were plowed, leveled, and harrowed for planting. Biodegradable films were placed on ridges and sides, and bases were buried in the soil to depths of 3–5 cm. This procedure was repeated on ridges in 2013, 2014, 2015, and 2016.

An alfalfa cultivar (No. 3 Gannong) bred at Gansu Agricultural University was hand sown at 22.5 kg ha^{-1} in 2012. This cultivar was selected and developed for its attractive characteristics such as improved drought, pests, and disease resistance. At depths of 2–3 cm, four rows were sown in a 60-cm-deep furrow with 20-cm gaps between two rows (Fig. 1). The ridge-furrow rainwater harvesting plots had 10 furrows with 40 rows of alfalfa, while flat planting field had 66 rows of alfalfa. Hand weeding was done throughout alfalfa cultivation seasons. During weeding, care was taken

Table 1 Soil physical and chemical properties in the experimental field

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

to avoid damaging the ridges. Neither fertilizer nor irrigation was applied to fields since alfalfa is a nitrogen-fixing legume and very sensitive to excessive soil water. The study was conducted under rain-fed conditions and climate. Field management and weed, insect, and disease control were all vigorously undertaken, as these activities have a significant impact on alfalfa production and quality of fodder. Harvest management entails determining number of cuts per season, date of cut, maturity stage, and time between cuts. During initial flowering phase and senescence, alfalfa was manually cut in all plots twice in 2012 and three times in 2013, 2014, 2015, and 2016 with sickles close to the soil surface.

2.4 Sampling and Measurements

In all experimental plots, soil samples were taken from 0 to 20, 20 to 40, and 40 to 60 cm and subsequently at 10-cm intervals at 300 cm soil layer with a soil auger to measure gravimetric soil water content (SWC). Readings on soil water content and moisture were recorded 24 h after every rainfall surpassed 5 mm (Hu et al. 2020). After undisturbed soil samples were dried in an oven at 105 °C for 24 h, bulk density (ρ) for 0–20 cm soil depth was determined (Verheijen et al. 2019). Alfalfa fodder samples (0.6 m×0.6 m) were harvested from ridge-furrow rainwater harvesting and flat planting plots and weighed in kilograms. The weight of sample was then multiplied by total area of plot divided by area of sample collection. The value obtained was then converted to kilograms per hectare (0.0001 kg m^{-2}=1 kg ha^{-1}) to determine fodder yield. Approximately 1 kg of dried fodder sample was ground in a rotary mill to move through a 1-mm laboratory inspection screen to assess consistency of alfalfa fodder, as previously described by Wang et al. (2019). The Kjeldahl method was used to estimate total nitrogen (Total N) (Sebnie et al. 2020), and crude protein (CP) was calculated by multiplying nitrogen (%) by the constant factor of 6.25 to convert nitrogen values to crude protein (CP) (AOAC 2005; Rodrigues et al. 2018). Acid detergent fiber (ADF) and neutral detergent fiber (NDF) were evaluated using procedures by Grzegorczyk et al. (2017).

2.5 Crop Water Consumption, Water Use Efficiency, Soil Desiccation Index, and Cost–Benefit Analysis

2.5.1 Crop Water Consumption and Water Use Efficiency

Using the modified water balance formula developed by Mo et al. (2017), total actual crop water consumption (CWC, mm) and water use efficiency (WUE (kg ha^{-1} mm^{-1})) of alfalfa fodder yield for the growing seasons were calculated as

$$CWC = P + \left(W_1 - W_2\right) \quad (1)$$

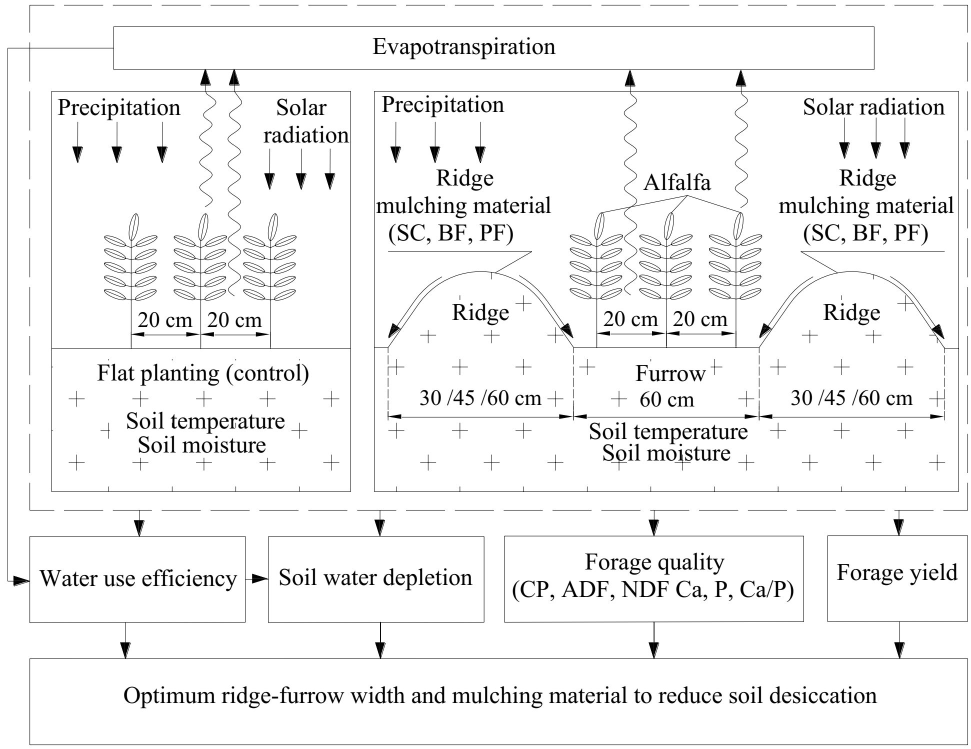

Fig. 1 Schematic diagram showing alfalfa production in ridge-furrow rainwater harvesting. FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with bio-degradable film, and plastic film, respectively

$$\mathrm{WUE} = \mathrm{Y}/\mathrm{CWC} \tag{2}$$

where P is total alfalfa growing season precipitation (mm), W_1 (mm) and W_2 (mm) are amounts of soil water storage measured 1 day before sowing and after last cutting for all treatments, and Y is the fodder yield (kg ha^{-1}). In addition, percolation and groundwater recharge are almost non-existent in this region (Ilstedt et al. 2016). Soil water storage

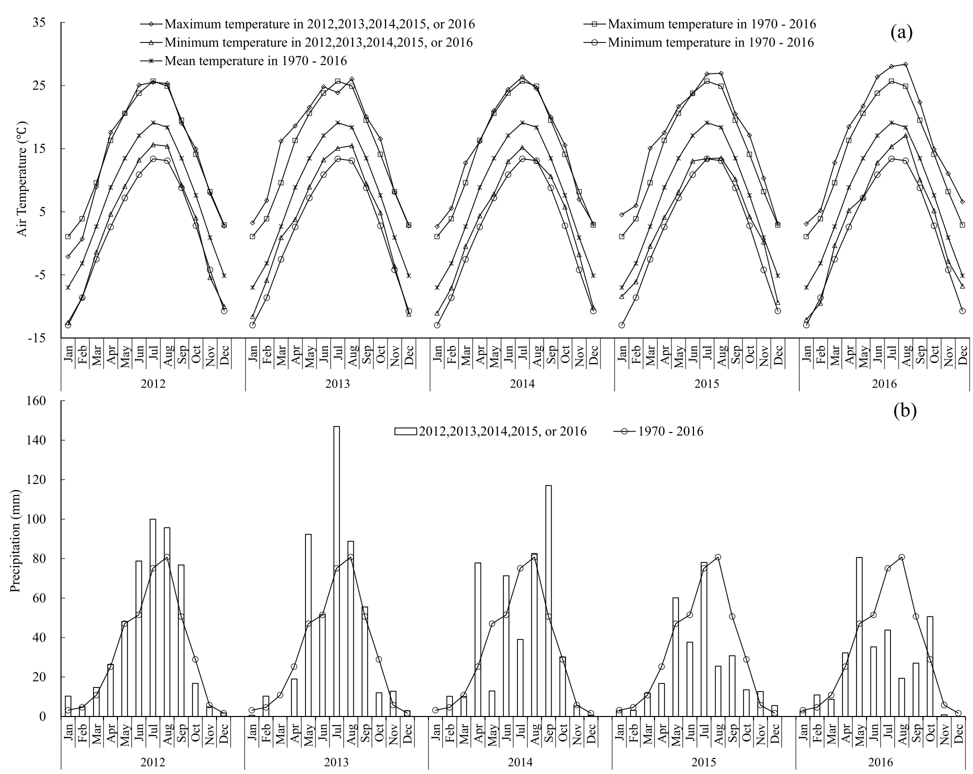

Fig. 2 Panel (**a**) shows mean monthly air temperature and panel (**b**) shows precipitation compared with the mean 46-year records (1970–2016) at the experiment site from 2012 to 2016

in soil layers (W_1 and W_2) was calculated according to Mo et al. (2017) as:

$$W = (\theta/100) \times \rho \times h \quad (3)$$

where θ is the soil water content (% kg kg^{-1}), ρ the bulk density (g cm^{-3}), and h is soil layer thickness (mm).

The soil water storage deficit (Da, mm) and degree of soil water deficit (DSW, %) were estimated as follows (Sun et al. 2018):

$$Da = Fc - SWS \quad (4)$$

where Fc is field capacity (mm) and SWS is soil water storage (mm) in 300 cm depth.

$$DSW = (Da/Fc) \times 100 \quad (5)$$

Soil water depletion was calculated using the formula by Jin et al. (2019):

$$\Delta W = SWS_{final} - SWS_{initial} \quad (6)$$

$SWS_{initial}$ is soil water storage (mm) before green-up, and SWS_{final} is soil water storage (mm) after last cutting.

2.5.2 Soil Desiccation Index

The quantity of soil water content or moisture held in the soil for 2–3 days after surplus water has been purged away, and rate of decreasing water after a rainfall event is termed as field capacity (Fc) (Rai et al. 2017). Hence, in this study, maximum SWC in a growing year for studied profiles was assumed to be equivalent to volumetric Fc (θ_{Fc}) of the year. Therefore, to obtain a more accurate and quantitative expression of the degree of soil water deficit, SDI was calculated following (Wang and Wang 2018):

$$SDI = \left(\frac{\theta_{Fc} - \theta_o}{\theta_{Fc} - \theta_{pwp}} \right) \times 100(\%) \quad (7)$$

where SDI is soil desiccation index and represents degree of soil water deficit, θ_{Fc} is volumetric field capacity, θ_o is current SWC, and θ_{pwp} is SWC at permanent wilting point. The intensity of soil desiccation was segmented into four degrees based on values of calculated soil desiccation indices: severe soil water deficit, when SDI value is > 50%; moderate soil water deficit, when SDI value is 25–50%; minor soil water deficit, when SDI value is 0–25%; and no deficit, when SDI value is < 0 (Jin et al. 2019).

2.5.3 Cost–Benefit Analysis

The cost–benefit analysis included an assessment of total costs, income from hay sales, and net economic benefit (NEB). The total costs included cost of seed, biodegradable film, and plastic film. Income here refers to income from fodder yield. However, these estimates did not take into account fixed costs, such as value of land, interest on capital, or depreciation. Labor was self-provided at zero cost for ridging, cross-ties, weeding, application of biodegradable and plastic film mulches, and other sampling operations. The major output considered in this analysis was alfalfa fodder yield. The NEB was calculated by subtracting input cost from fodder yield income (Guo et al. 2019).

2.5.4 Statistical Analysis

Summary statistics of means (θ), standard deviations (SDs), ANOVA, and effects of treatments were computed using one-way Duncan's procedure in SPSS software (version 26, IBM Corp., Chicago, IL, USA).

3 Results

3.1 Air Temperature and Rainfall

During alfalfa cultivation seasons (April–October), air temperatures were 21.2 (2012), 21.6 (2013), 21.1 (2014), 22.0 (2015), and 20.7 °C (2016), respectively. Compared to reference mean per annum temperature of 14.2 ℃, yearly air temperature was 13.9 (2012), 15.7 (2013), 14.9 (2014), 16.1 (2015), and 16.6 ℃ (2016) (Fig. 2a). This depicts a slightly higher air temperature during the alfalfa growing seasons.

Rainfall data showed a declining trend over the study period. Mean rainfall was 478.9 (2012), 492.8 (2013), 457.2 (2014), 298.2 (2015), and 311.95 mm (2016), while total rainfall (April–October) was 442.6 mm (2012), 466.2 mm (2013), 430.8 mm (2014), 262.3 mm (2015), and 288.85 mm (2016), respectively (Fig. 2b). Compared to the reference mean annum rainfall records of 385.3 mm, the mean rainfall for 5-year alfalfa cultivation seasons was 359.3 mm. This indicates a slightly decreasing trend in rainfall over the growing periods of alfalfa.

Rainfall in CS_{30} (3.27 and 4.94) was the highest as PF_{60} (0.04 and 1.30) had the lowest threshold rainfall in 2012 and 2016, respectively, when compared to flat planting. In 2013 and 2014, however, the highest threshold rainfall was recorded in CS_{30} (6.83 and 3.70) as the lowest was observed in BF_{60} (1.11 and 0.02), respectively. Furthermore, the highest threshold rainfall was recorded in CS_{45} (5.30), as PF_{60} (0.75) produced the lowest threshold rainfall when compared to flat planting treatment in 2015. Consequently, the proportion of variation between runoff and rainfall from 2012 to 2016 was the highest in PF with $R^2 = 1.00$ and the lowest in CS with $R^2 = 0.56$ (Fig. 3a). This suggests that PF treatment has an advantage in flood prevention which might ultimately lead to runoff compared to CS, BF, and flat planting treatments. This indicates the effectiveness of plastic film mulching in ridge-furrow rainwater harvesting system in conserving water under rain-fed agriculture.

3.2 Crop Water Consumption

Crop water consumption in CS_{45}, CS_{60}, and PF_{60} deceased during alfalfa cultivation in 2012, 2014, and 2015, respectively. In 2013, crop water consumption was greatly reduced in PF_{60} as compared to CS_{45}, while in 2016; BF_{30} had the highest increase in CWC compared to BF_{60} which had the lowest increase in CWC. In 2012, mean CWC for FP was significantly higher than that for BF (mean of BF_{30}, BF_{45}, and BF_{60}), and no significant ($p > 0.05$) differences were found between CS and FP. In 2013, CWC in FP was significantly higher than in PF, and no significant ($p > 0.05$) differences were established between BF and PF. Contrarily, in 2014, CWC in BF was significantly ($p < 0.05$) higher than that in FP, and no significant differences were found between BF and PF. In 2015 and 2016, CWC in BF was significantly ($p < 0.05$) higher than that in FP (Table 2). Consequently, over the 5 years of alfalfa cultivation, CWC decreased by 2.35% on average, ranging from 419.16 to 436.98 mm relative to flat planting. This implies that plastic film mulching in ridge-furrow rainwater harvesting system is effective in reducing soil water loss in rain-fed agriculture.

3.3 Soil Desiccation

Compared to CS and PF, soil water deficit (Da) was higher in FP and was lower in BF in 2012. This led to FP

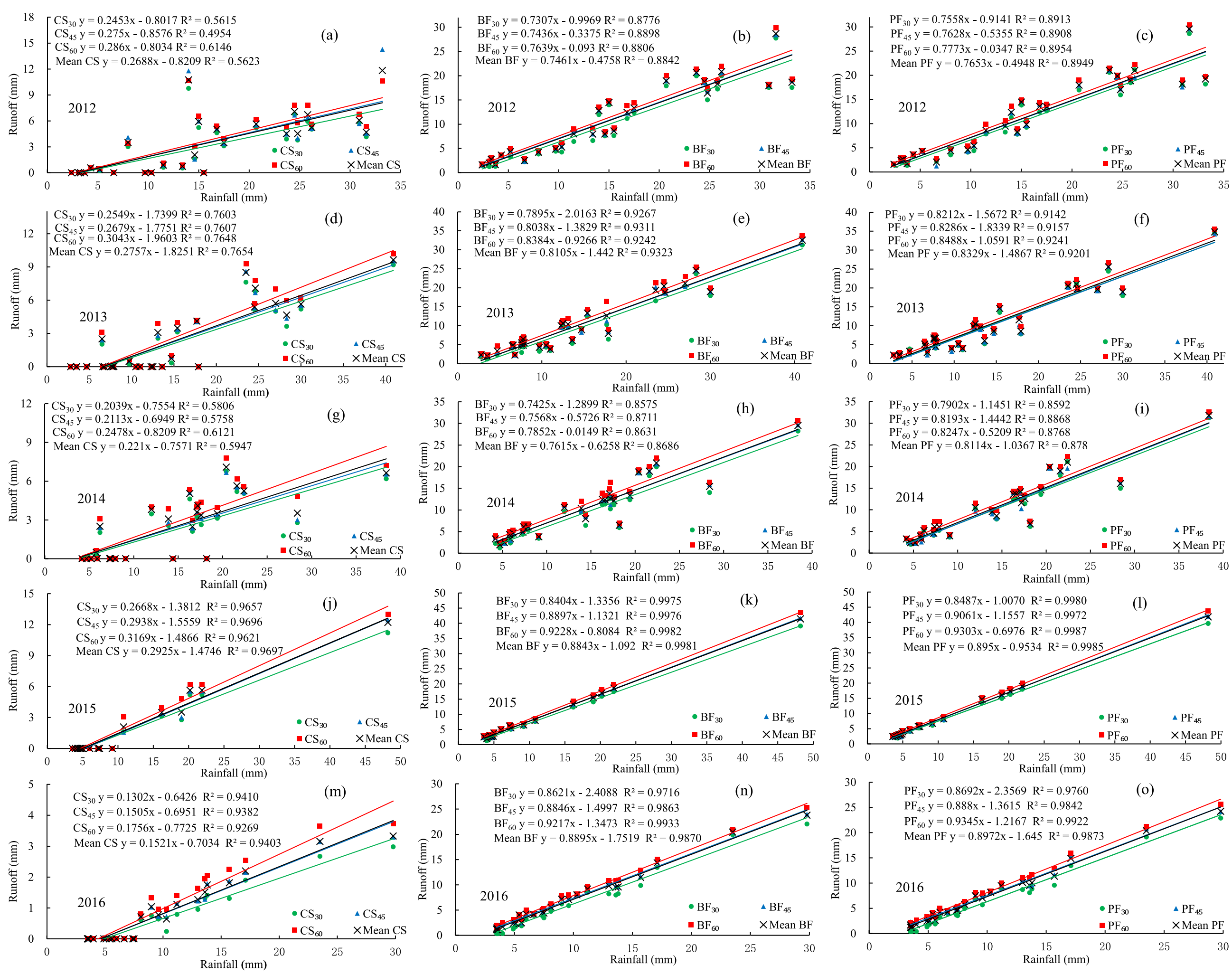

Fig. 3 Panels (**a**)–(**c**), (**d**)–(**f**), (**g**)–(**i**), (**j**)–(**l**), and (**m**)–(**o**) show rainfall-runoff relationship during alfalfa growing season in 2012, 2013, 2014, 2015, and 2016, respectively, for ridges with manually compacted soil, mulched with bio-degradable film, and plastic film. The ridge widths of CS30, CS45, and CS60 (BF30, BF45 and BF60 or PF30, PF45 and PF60) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

Table 2 Crop water consumption (mm) of alfalfa production in ridge-furrow rainwater harvesting from 2012 to 2016

Treatment	2012	2013	2014	2015	2016	Average
FP	541.04 ± 18a	579.18 ± 19a	406.35 ± 13b	327.49 ± 11a	336.56 ± 11a	438.12 ± 104a
CS_{30}	513.97 ± 19cba	527.16 ± 20b	445.19 ± 16ba	335.08 ± 12a	352.75 ± 13a	434.83 ± 79a
CS_{45}	535.75 ± 18ba	530.24 ± 17b	427.94 ± 14ba	334 ± 11a	356.97 ± 12a	436.98 ± 84a
CS_{60}	501.41 ± 8cb	524.28 ± 9b	424.02 ± 7ba	336.28 ± 5a	359.24 ± 6a	429.04 ± 75a
BF_{30}	481.5 ± 12c	521.11 ± 13b	446.58 ± 11ba	341.01 ± 8a	362.44 ± 9a	430.53 ± 69a
BF_{45}	473.09 ± 20dc	499.41 ± 21b	455.4 ± 19a	334.72 ± 14a	360.79 ± 15a	424.68 ± 65a
BF_{60}	442 ± 19d	507.27 ± 22b	458.39 ± 19a	356.58 ± 15a	347.11 ± 15a	422.27 ± 61a
PF_{30}	491.35 ± 16c	525.34 ± 17b	451.2 ± 14a	336.94 ± 11a	349.88 ± 11a	430.94 ± 75a
PF_{45}	489.16 ± 16c	495.53 ± 17b	437.1 ± 14ba	340.13 ± 11a	347.71 ± 11a	421.93 ± 67a
PF_{60}	474.63 ± 16dc	493.73 ± 16b	451.88 ± 15a	325.11 ± 11a	350.45 ± 11a	419.16 ± 68a
Mean						
FP	541.04 ± 18a	579.18 ± 19a	406.35 ± 13b	327.49 ± 11a	336.56 ± 10.99b	438.12 ± 104a
CS	517.04 ± 21a	527.22 ± 16b	432.38 ± 16a	335.12 ± 10a	356.32 ± 10.95a	433.62 ± 80ab
BF	465.53 ± 24b	509.26 ± 21b	453.45 ± 18a	344.1 ± 16a	356.78 ± 14.87a	425.83 ± 65ab
PF	485.05 ± 19b	504.86 ± 22b	446.73 ± 16a	334.06 ± 13a	349.35 ± 11.38ba	424.01 ± 70b

Values are means ± standard errors. Means within a column followed by the same letters are not significantly different at the 5% level (one-way Tukey test's analysis of variance). FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with bio-degradable film, and plastic film, respectively. The ridge widths of CS_{30}, CS_{45}, and CS_{60} (BF_{30}, BF_{45}, and BF_{60} or PF_{30}, PF_{45}, and PF_{60}) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

recording significantly ($p < 0.05$) higher mean soil desiccation compared to BF (mean of BF_{30}, BF_{45}, and BF_{60}). Additionally, soil desiccation from 2013 to 2016 was significantly higher in FP than in PF (mean of PF_{30}, PF_{45}, and PF_{60}). Consequently, moderate soil desiccation was found in CS (43.03%) while PF_{60} had the lowest soil water deficit (12.42 mm). The soil water depletion (-0.49 m^3 m^{-3}) recorded in CS led to severe soil desiccation of 53.54% in 2013. Mean soil water depletion (ΔW) decreased by 0.54 in BF treatments compared to FP (Fig. 4b, d, e), suggesting moderate desiccation in BF treatment. Conversely, FP significantly increased the degree of soil water deficit (DSW) by 60.22% indicating severe desiccation while DSW was impacted by PF with moderate desiccation of 49.91% (Fig. 4b, c, d, e). This confirms that plastic film mulching in ridge-furrow rainwater harvesting reduces soil desiccation in alfalfa production under rain-fed conditions in semiarid areas.

3.4 Fodder Yield and Water Use Efficiency

Alfalfa fodder yield increased gradually from April to June 2012 and from July to September 2012; fodder yield increased progressively after sowing in both ridge–furrow rainwater harvesting (RFRH) and FP. This trend occurred in subsequent years with yields in RFRH treatments substantially higher than those in FP. In 2012 and 2013, yield decreased in BF_{60} (2.02%) and CS_{30} (0.83%) as compared to increase in yield in PF_{45} (16.05%) and PF_{30} (43.4%), respectively. Conversely, in 2014 and 2015, yield was decreased by 4.8 and 9.1% in CS_{45} and increased by 64.11 and 62.7% in PF_{30} relative to FP, respectively. In 2016, however, yield increased in PF_{45} by 22.3% and decreased in CS_{60} by 1.5% compared to FP (Table 3). On average, CS had no increase in yield of alfalfa over the 5 years growing period, while BF and PF had a 28% and 33% yield increase compared to FP. In addition, average mean yield increase over the 5 years ranked PF > BF > FP > CS. This implies that, averagely, plastic film mulched ridge-furrow rainwater harvesting with 30 cm ridge width is efficient in increasing alfalfa fodder yield under rain-fed conditions.

Conversely, water use efficiency (WUE) decreased in CS_{30} in 2012 and 2013 and correspondingly increased in PF_{45} and PF_{30} (Table 3). Again, in 2014 and 2015, PF_{30} had the highest increase in WUE while CS_{45} and CS_{60} had a decrease in WUE. However, in 2016, WUE was increased in PF_{45} but decreased in CS_{45} during the alfalfa growing seasons. Over the 5 years of alfalfa cultivation, WUE increased by 19.79% on average and was highest in PF_{30} by 28.19 kg ha^{-1} mm^{-1} relative to flat planting. This suggests that plastic film mulched ridge-furrow rainwater harvesting with 30 cm ridge width is efficient in increasing alfalfa water use efficiency under rain-fed conditions.

3.5 Fodder Quality

We assessed how the treatments affected nutrient compositions of alfalfa fodder by analyzing the fodder quality. Crude protein (CP) in PF_{60} was 196 g kg^{-1} and 214 g kg^{-1} in 2012 and 2015, respectively, while in 2013, 2014, and 2016, CP

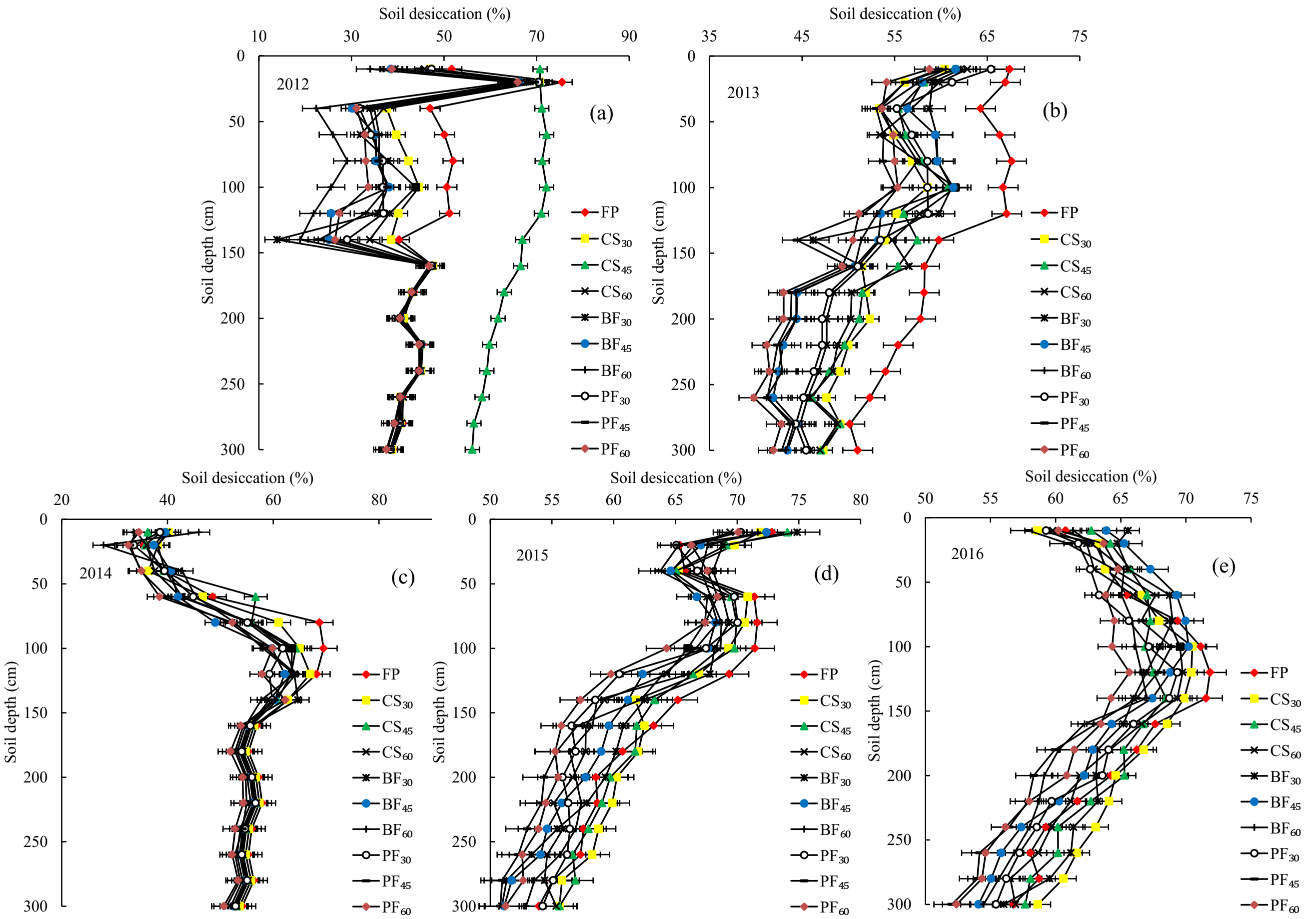

Fig. 4 Panels (**a**)–(**e**) show soil profile distribution of soil desiccation in 2012, 2013, 2014, 2015, and 2016, respectively, after the last cutting. FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with biodegradable mulch film, and plastic film, respectively. The ridge widths of CS30, CS45 and CS60 (BF30, BF45 and BF60 or PF30, PF45, and PF60) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

was 217, 215, and 189 g kg^{-1} in BF$_{60}$, respectively (Table 4). This indicates a significant increase in PF (28.77%; $p<0.05$) relative to FP, CS, and BF. In terms of acid detergent fiber (ADF), flat planting (FP) had 394 g kg^{-1} ADF as the highest, and BF treatments had the lowest mean ADF of 348 g kg^{-1}, with BF$_{60}$ recording 345 g kg^{-1} mean ADF. This implies that flat planting increased ADF during the alfalfa growing seasons. A similar trend was found for neutral detergent fiber (NDF). Flat planting had the highest NDF (505 g kg^{-1}) while BF treatments had the lowest mean NDF of 471 g kg^{-1} with BF$_{45}$ and BF$_{60}$ recording 466 g kg^{-1} each. Averagely, among all treatments of alfalfa cultivation over 5 years, CP ranged from 169 to 202 g kg^{-1}, ADF ranged from 338 to 394 g kg^{-1}, and NDF ranged from 464 to 505 g kg^{-1}. As demonstrated by this study, CP was significantly ($p<0.05$) higher in PF treatments with FP recording the highest mean ADF and NDF compared to CS and BF. This suggests that plastic film mulched ridge-furrow rainwater harvesting with 60 cm ridge width is efficient in increasing alfalfa fodder crude protein content under rain-fed conditions.

3.6 Cost–Benefit Analysis

Smallholder farmers have less income to adopt two ridge widths to determine which is more beneficial to them; hence, we conducted an economic benefit analysis as different mulching materials were used with variances in input costs of the mulching materials (Table 5). The average input cost (US Dollar (US$)) over 5 years was rated as follows: BF > PF > CS > FP. The average input cost values under BF and PF were 245.16 and US$148.87 ha^{-1}, respectively, higher than CS and FP. The plots' most important output value was fodder yield, which had a consistent market price (local price) between and within experimental seasons. In this study, output values from 2012 to 2016 for various treatments were ranked as PF > BF > FP > CS per net income.

Table 3 Fodder yield (kg ha^{-1}) and water use efficiency (WUE) (kg ha^{-1} mm^{-1}) of alfalfa in ridge-furrow rainwater harvesting from 2012 to 2016

Treatments	2012		2013		2014		2015		2016		Average		
	Yield	WUE	Yield	WUE	Yield	WUE	Yield	WUE	Yield	WUE	Yield	Yield increase %	WUE
FP	4112 ± 127d	9.680 ± 1b	8440 ± 228e	18.40 ± 1c	7178 ± 162a	16.76 ± 1f	7377 ± 140f	23.40 ± 1e	9657 ± 273e	32.23 ± 1e	7353 ± 1845 h	0	20.09 ± 7 h
CS_{30}	3794 ± 187e	9.78 ± 1b	8370 ± 287e	19.35 ± 1c	8500 ± 353bc	24.41 ± 2e	8848 ± 494ef	27.40 ± 2de	9233 ± 47e	29.23 ± 1e	7749 ± 1977 g	5	22.03 ± 7 g
CS_{45}	3373 ± 82f	9.00 ± 1b	7916 ± 382ef	17.97 ± 1 cd	7523 ± 309ab	17.87 ± 1f	8050 ± 556ef	25.02 ± 2cde	10,185 ± 34de	31.82 ± 1d	7409 ± 2221 g	1	20.34 ± 8 g
CS_{60}	3026 ± 103 g	8.15 ± 1b	7371 ± 234f	16.49 ± 1d	6825 ± 305a	16.45 ± 1f	7802 ± 227de	24.07 ± 1 cd	9508 ± 20 fg	29.50 ± 1d	6906 ± 2137f	-6	18.93 ± 7f
BF_{30}	4241 ± 131 cd	12.17 ± 1a	11,697 ± 477a	26.93 ± 1a	11,543 ± 487f	25.64 ± 1bc	11,301 ± 346bc	34.37 ± 1c	10,744 ± 115c	33.00 ± 1d	9905 ± 2850e	35	26.42 ± 8e
BF_{45}	4517 ± 132b	13.15 ± 1a	10,729 ± 257bc	24.80 ± 2b	10,305 ± 389de	24.13 ± 2 cd	10,462 ± 486b	32.44 ± 2b	11,403 ± 139ab	35.21 ± 1c	9483 ± 2511d	29	25.95 ± 8d
BF_{60}	4195 ± 93d	13.38 ± 1a	9997 ± 399d	23.41 ± 1b	9317 ± 89 cd	21.47 ± 1e	9573 ± 447ab	27.80 ± 1b	11,123 ± 238bc	35.86 ± 1bc	8841 ± 2403c	20	24.38 ± 7 cd
PF_{30}	4472 ± 72bc	12.30 ± 1a	12,104 ± 271a	27.17 ± 1a	11,780 ± 578f	27.78 ± 2a	12,001 ± 63 cd	36.95 ± 1ab	11,500 ± 95ab	36.74 ± 1bc	10,371 ± 2956b	41	28.19 ± 9c
PF_{45}	4772 ± 87a	13.22 ± 1a	11,016 ± 173b	24.73 ± 1b	10,669 ± 63ef	26.96 ± 2ab	11,406 ± 153ab	34.78 ± 1ab	11,806 ± 141a	37.98 ± 1ab	9934 ± 2608b	35	27.54 ± 9b
PF_{60}	4328 ± 55bcd	12.55 ± 1a	10,209 ± 216 cd	23.77 ± 1b	9574 ± 73cde	23.03 ± 1de	10,314 ± 427bc	32.96 ± 1a	11,292 ± 133ab	36.01 ± 1a	9143 ± 2469a	24	25.67 ± 8a
Mean													
FP	4112 ± 127b	9.68 ± 1b	8440 ± 228b	18.40 ± 1b	7178 ± 162a	16.76 ± 1b	7377 ± 140b	23.40c ± 1	9657 ± 273b	32.23 ± 1d	7353 ± 1845 b	0	20.09 ± 7b
CS	3397 ± 3440c	8.98 ± 1b	7886 ± 388c	17.94 ± 2b	7616 ± 759a	18.58 ± 4b	8028 ± 633b	25.50 ± 2c	9778 ± 401b	30.18 ± 1c	7341 ± 2136 b	0	20.43 ± 1b
BF	4318 ± 186ab	12.90 ± 1a	10,808 ± 797a	25.04 ± 3a	10,388 ± 980a	23.75 ± 2a	10,160 ± 826a	31.54 ± 3b	11,205 ± 320a	34.69 ± 1b	9376 ± 2632a	28	25.58 ± 1a
PF	4524 ± 198a	12.69 ± 1a	11,110 ± 808a	25.22 ± 2a	10,674 ± 962a	25.92 ± 3a	10,987 ± 747a	34.90 ± 2a	11,544 ± 245a	36.91 ± 1a	9768 ± 2733a	33	27.13 ± 1a

Values are means ± standard errors. Means within a column followed by the same letters are not significantly different at the 5% level (one-way Tukey test's Analysis of variance). FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with bio-degradable film, and plastic film, respectively. The ridge widths of CS_{30}, CS_{45}, and CS_{60} (BF_{30}, BF_{45}, and BF_{60} or PF_{30}, PF_{45}, and PF_{60}) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

Table 4 Crude protein (CP) (g kg^{-1}), neutral detergent fiber (NDF) (g kg^{-1}), and acid detergent fiber (ADF) (g kg^{-1}) of alfalfa in ridge-furrow rainwater harvesting from 2012 to 2016

Treatments	2012			2013			2014			2015			2016			Average		
	CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF	CP	ADF	NDF
FP	146 ± 10c	307 ± 20a	407 ± 27a	182 ± 12b	385 ± 25a	488 ± 32a	175 ± 11d	408 ± 28a	526 ± 34a	170 ± 3b	419 ± 12a	544 ± 8a	160 ± 7b	437 ± 7a	55 ± 11a	169 ± 12d	394 ± 47a	505 ± 55a
CS_{30}	153 ± 8c	292 ± 16b	395 ± 21a	191 ± 10b	370 ± 20b	471 ± 25b	179 ± 10d	396 ± 21ab	516 ± 27ab	174 ± 4ab	407 ± 10ab	534 ± 13ab	165 ± 1ab	425 ± 7bc	555 ± 11ab	178 ± 14 cd	369 ± 40b	491 ± 54ab
CS_{45}	153 ± 10c	290 ± 18b	394 ± 25a	205 ± 13a	364 ± 23bc	467 ± 29bc	182 ± 11d	387 ± 24abc	511 ± 32abc	178 ± 11ab	397 ± 10abc	526 ± 5ab	177 ± 4ab	422 ± 9c	545 ± 6ab	183 ± 18bcd	361 ± 37bc	486 ± 51bc
CS_{60}	153 ± 9c	290 ± 16b	389 ± 22a	206 ± 12a	356 ± 20 cd	459 ± 26 cd	180 ± 10d	378 ± 21bcd	514 ± 29ab	180 ± 16ab	390 ± 23abc	530 ± 6ab	182 ± 26ab	405 ± 28 cd	546 ± 7ab	180 ± 18 cd	361 ± 38bc	485 ± 55bc
BF_{30}	178 ± 10b	283 ± 16b	387 ± 22a	206 ± 12a	360 ± 20bc	465 ± 26bc	194 ± 11c	356 ± 20def	505 ± 29abcd	191 ± 16ab	366 ± 13 cd	519 ± 3ab	185 ± 6ab	391 ± 8a	534 ± 9ab	190 ± 14abc	353 ± 38bcd	480 ± 51bcd
BF_{45}	183 ± 12ab	281 ± 18b	383 ± 25a	214 ± 14a	355 ± 23 cd	455 ± 30d	205 ± 13b	360 ± 24de	491 ± 32cde	195 ± 4ab	371 ± 8bcd	506 ± 6ab	187 ± 10ab	388 ± 7ab	522 ± 7ab	195 ± 17ab	346 ± 33 cd	466 ± 45de
BF_{60}	185 ± 10ab	283 ± 15b	370 ± 20a	217 ± 12a	347 ± 18de	443 ± 24e	215 ± 11a	345 ± 18ef	488 ± 26de	199 ± 18ab	357 ± 38 cd	503 ± 32ab	189 ± 14ab	379 ± 37abc	516 ± 20b	196 ± 17ab	345 ± 34 cd	466 ± 55de
PF_{30}	178 ± 12ab	285 ± 19b	373 ± 24a	206 ± 14a	356 ± 23 cd	460 ± 30 cd	193 ± 13c	363 ± 24cde	495 ± 32bcde	188 ± 9ab	375 ± 7bcd	512 ± 11ab	171 ± 10ab	387 ± 10c	526 ± 9ab	186 ± 12bc	365 ± 47bc	483 ± 64bc
PF_{45}	190 ± 11ab	279 ± 16b	370 ± 21a	211 ± 12a	349 ± 20de	452 ± 26de	201 ± 11bc	346 ± 20ef	495 ± 28bcde	190 ± 10ab	358 ± 9 cd	511 ± 3ab	177 ± 5ab	384 ± 8 cd	522 ± 14ab	198 ± 8ab	344 ± 36 cd	470 ± 55cde
PF_{60}	196 ± 13a	278 ± 18b	369 ± 24a	216 ± 14a	344 ± 23e	442 ± 29e	217 ± 14a	333 ± 22f	480 ± 31e	214 ± 17a	342 ± 7d	495 ± 14b	199 ± 15a	353 ± 14d	512 ± 14b	202 ± 15a	338 ± 33d	464 ± 54e
Mean																		
FP	146 ± 10b	307 ± 20a	407 ± 27a	182 ± 12c	385 ± 25a	488 ± 32a	175 ± 11b	408 ± 27a	526 ± 34a	170 ± 3b	419 ± 12b	544 ± 8c	160 ± 7b	437 ± 7b	559 ± 11b	160 ± 12c	394 ± 47a	505 ± 55a
CS	153 ± 9b	291 ± 17b	393 ± 23ab	201 ± 14b	363 ± 22b	465 ± 27b	181 ± 11b	387 ± 23b	514 ± 30a	178 ± 13ab	398 ± 17b	530 ± 11bc	175 ± 19ab	417 ± 18b	548 ± 8b	180 ± 17b	364 ± 39b	487 ± 53b
BF	182 ± 11a	282 ± 17bc	380 ± 23b	212 ± 13a	354 ± 21c	454 ± 28c	205 ± 15a	354 ± 22c	495 ± 30b	195 ± 15a	365 ± 24a	509 ± 21ab	187 ± 11a	386 ± 23a	524 ± 16a	194 ± 16a	348 ± 35b	471 ± 51c
PF	188 ± 14a	281 ± 18c	371 ± 23b	211 ± 14a	349 ± 22c	451 ± 29c	204 ± 16a	347 ± 25c	490 ± 31b	198 ± 17a	359 ± 17a	506 ± 15a	182 ± 13a	374 ± 25a	520 ± 23a	195 ± 13a	349 ± 41b	472 ± 59c

Values are means ± standard errors. Means within a column followed by the same letters are not significantly different at the 5% level (one-way Tukey test's Analysis of variance). FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with bio-degradable film, and plastic film, respectively. The ridge widths of CS_{30}, CS_{45}, and CS_{60} (BF_{30}, BF_{45}, and BF_{60} or PF_{30}, PF_{45}, and PF_{60}) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

Table 5 Cost–benefit analysis (USD ha^{-1}) of alfalfa production in ridge-furrow rainwater harvesting from 2012 to 2016

Year	Treatment	Inputs				Revenue yield	Net economic benefit	Benefit/cost ratio
		Seed	Plastic film	Biodegradable film	Total cost			
2012	FP	85.13	0.00	0.00	85.12	1379.91	1294.79	16.21
	CS_{30}	84.75	0.00	0.00	84.75	1138.50	1053.75	13.43
	CS_{45}	84.99	0.00	0.00	84.99	1140.40	1055.40	13.42
	CS_{60}	85.64	0.00	0.00	85.63	1141.01	1055.38	13.33
	BF_{30}	83.97	0.00	47.45	131.43	1446.74	1315.31	11.01
	BF_{45}	84.88	0.00	47.85	132.73	1448.29	1315.57	10.91
	BF_{60}	86.52	0.00	51.79	138.31	1452.08	1313.78	10.50
	PF_{30}	82.04	25.79	0.00	107.83	1514.94	1407.11	14.05
	PF_{45}	86.00	30.23	0.00	116.23	1518.83	1402.59	13.07
	PF_{60}	87.31	33.30	0.00	120.62	1520.73	1400.11	12.61
2013	FP	85.13	0.00	0.00	85.12	2832.30	2747.18	33.27
	CS_{30}	84.29	0.00	0.00	84.30	2644.11	2559.82	31.37
	CS_{45}	84.73	0.00	0.00	84.73	2646.24	2561.51	31.23
	CS_{60}	86.35	0.00	0.00	86.35	2648.82	2562.47	30.68
	BF_{30}	80.38	0.00	47.08	127.46	3624.87	3497.40	28.44
	BF_{45}	86.38	0.00	48.83	135.21	3627.40	3492.20	26.83
	BF_{60}	88.61	0.00	51.18	139.79	3628.60	3488.81	25.96
	PF_{30}	83.39	26.46	0.00	109.85	3726.44	3616.59	33.92
	PF_{45}	84.24	30.90	0.00	115.14	3727.75	3612.61	32.38
	PF_{60}	87.74	31.97	0.00	119.70	3730.72	3611.01	31.17
2014	FP	85.13	0.00	0.00	85.12	2408.80	2323.68	28.30
	CS_{30}	84.20	0.00	0.00	84.19	2555.02	2470.83	30.35
	CS_{45}	85.54	0.00	0.00	85.55	2555.61	2470.06	29.87
	CS_{60}	85.64	0.00	0.00	85.63	2556.73	2471.09	29.86
	BF_{30}	81.44	0.00	46.06	127.50	3483.68	3356.17	27.32
	BF_{45}	86.65	0.00	49.68	136.33	3487.04	3350.71	25.58
	BF_{60}	87.27	0.00	51.35	138.62	3487.32	3348.69	25.16
	PF_{30}	82.14	26.87	0.00	109.00	3581.63	3472.62	32.86
	PF_{45}	85.00	29.63	0.00	114.64	3581.85	3467.21	31.24
	PF_{60}	88.23	32.82	0.00	121.05	3582.49	3461.44	29.60
2015	FP	85.13	0.00	0.00	85.12	2475.58	2390.46	29.08
	CS_{30}	84.29	0.00	0.00	84.30	2691.91	2607.62	31.93
	CS_{45}	84.47	0.00	0.00	84.46	2694.01	2609.55	31.90
	CS_{60}	86.62	0.00	0.00	86.61	2696.21	2609.59	31.13
	BF_{30}	84.09	0.00	46.10	130.19	3406.89	3276.70	26.17
	BF_{45}	84.59	0.00	49.87	134.47	3410.71	3276.25	25.36
	BF_{60}	86.68	0.00	51.12	137.80	3410.90	3273.09	24.75
	PF_{30}	84.34	27.86	0.00	112.20	3684.84	3572.64	32.84
	PF_{45}	85.43	30.71	0.00	116.14	3686.70	3570.56	31.74
	PF_{60}	85.59	30.75	0.00	116.35	3689.54	3573.19	31.71
2016	FP	85.13	0.00	0.00	85.12	3240.70	3155.58	38.07
	CS_{30}	83.48	0.00	0.00	83.48	3279.23	3195.75	39.28
	CS_{45}	83.63	0.00	0.00	83.63	3280.55	3196.93	39.23
	CS_{60}	88.26	0.00	0.00	88.26	3284.14	3195.88	37.21
	BF_{30}	84.10	0.00	46.90	131.00	3759.50	3628.50	28.70
	BF_{45}	84.53	0.00	49.17	133.69	3759.93	3626.23	28.12
	BF_{60}	86.74	0.00	51.03	137.77	3761.13	3623.36	27.30
	PF_{30}	84.29	28.04	0.00	112.32	3872.32	3760.00	34.48
	PF_{45}	84.43	29.77	0.00	114.21	3872.89	3758.68	33.91
	PF_{60}	86.65	31.52	0.00	118.16	3876.62	3758.46	32.81

FP, CS, BF, and PF were abbreviated for flat planting, ridges with manually compacted soil, mulched with bio-degradable film, and plastic film, respectively. The ridge widths of CS_{30}, CS_{45}, and CS_{60} (BF_{30}, BF_{45}, and BF_{60} or PF_{30}, PF_{45}, and PF_{60}) were 30, 45, and 60 cm, respectively, with 60 cm furrow width for all treatments

The PF_{60} treatment registered the highest net economic benefit (NEB) throughout 5 years of alfalfa cultivation. This indicates that an investment in PF treatment with a 60 cm ridge width by a smallholder farmer is technically and economically viable.

4 Discussion

When rainfall becomes the only recorded climatic parameter, runoff, a rare but vital parameter for soil and water conservation research, becomes difficult to measure. Due to interception and initial high infiltration losses, a threshold rainfall is always required before runoff occurs. The threshold rainfall is the minimum amount of rainfall above which runoff occurs, calculated by plotting daily rainfall depth against corresponding runoff depth and fitting it with a least-square curve (Liu et al. 2020a). In this study, all ridge-furrow rainwater harvesting treatments had low threshold rainfalls for runoff, though threshold values increased slightly in ridges compacted with soil. Other studies in northern Ethiopia (He et al. 2018b; Li et al. 2017c; Milkias et al. 2018) corroborated findings of this study. Threshold rainfalls for previous studies range from 5 to 8 mm for short enclosures and 3 mm for grazing lands (Dao et al. 2020). Xin et al. (2021) reported a 2-mm rainfall threshold for cultivated land and ascribed it to lower infiltration capacity of soils in semiarid environments. The slight increase in rainfall thresholds in ridges compacted with soil is most likely attributable to water ponding in ridges and improved soil infiltration capacity due to reduced ridge widths.

Variability in amount and distribution of seasonal precipitation, which involves evaporation from soil surface and crop transpiration, is a major source of variation in CWC on the Loess Plateau (Do and Yin 2018). We recorded a 2.35% decrease in CWC in the ridge-furrow rainwater harvesting system with mulching over 5 years of alfalfa cultivation compared to flat planting. This is consistent with Zhao et al. (2018), who reported simulation of heat flow and soil water in RF with plastic film mulching, decreased CWC on Chinese Loess Plateau where plastic film mulching was less effective for increasing WUE in rain-fed agriculture. Furthermore, Dang et al. (2016) in 2015 reported 56.2% higher yield under plastic film-mulched ridge-furrow (RF), 63.4% higher WUE, and 15.0% lower water use (CWC) than FP, respectively. Plastic film mulching with RFRH markedly increases WUE and improves crop production as a potential soil amendment for sustainable rain-fed agriculture (Ding et al. 2019).

We assessed the effect of ridge-furrow rainwater harvesting treatments on alfalfa yield and soil desiccation over the 5 years. Mean soil desiccation in this study compared to FP decreased by 0.54 in BF treatment. This may be attributed to high weed control potential of biodegradable films (Marí et al. 2019), which decreases bulk density, hence increasing WUE and crop production (Gu et al. 2020). Additionally, Sekara et al. (2019) and Caruso et al. (2019) reported biodegradable films differentially influenced soil temperature and humidity. This could be beneficial in arid and semi-arid areas characterized by high temperatures that could damage crops. In this study, optimum ridge width in RFRH system to increase yield, improve WUE, and thus reduce soil desiccation was 60 cm for alfalfa production in northwestern China. Hu et al. (2020) reported that ultimate ridge and furrow width for increasing WUE in alfalfa production was 60 cm, thus corroborating our finding. Furthermore, Luo et al. (2021) also reported a ridge width of 0.3 m and a furrow width of 0.6 m for use in semi-arid areas for alfalfa production.

There are two technical components of RFRH system: rainwater harvesting and mulching. The system improves soil water content and soil temperature, prolongs period of moisture availability, assists in weed control, and enhances agricultural production (Zhang et al. 2019). Simultaneously, this technique uses contour ridges, which are intended to reduce runoff and soil erosion (Li et al. 2021). Alfalfa yield was increased by 33% in this study with plastic film, which could be due to lower crop water consumption in mulched fields. This is consistent with Gu et al. (2018), who reported a range of 10.7–40.3% increase in alfalfa yield in PF treatments and 14.2–28.3% decrease in alfalfa yield in CS treatments. There were higher and comparable yields in 2015 and 2016 under less rainfall conditions compared to yields recorded in 2013 and 2014. This may be attributed to the high-yielding ability of the alfalfa cultivar. In addition, continued field maintenance was undertaken in years following establishment to achieve high yields and sustain a desirable level of production over time. Furthermore, alfalfa is exceptionally drought resistant and does not require additional water to produce higher yields (Liu et al. 2018b). Alfalfa roots typically grow to a depth of 3–5 m and can reach up to 8–15 m in soils. Consequently, when surface water is scarce, alfalfa may depend on moisture stored deep in soil profiles (Jia et al. 2020). Furthermore, alfalfa's ability to use residual winter rainfall makes it possible to grow for 4–8 years and rapidly in warm conditions in spring. This is in contrast to summer-grown annual crops, which must be replanted every year (water use efficiency is low during this time) (Mak-Mensah et al. 2021c). Alfalfa is also valuable due to its deep rooting ability to exploit conserved soil moisture, ability to withstand droughts, and ability to produce high yields in drought conditions (Gruffat et al. 2020).

We evaluated treatment-specific effect of ridge-furrow rainwater harvesting on WUE and fodder quality over the 5 years. WUE correlated with fodder and grain yield per unit of alfalfa crop water consumption. In comparison with flat planting, plastic film mulched treatment increased mean WUE by 35% during alfalfa cultivation seasons. This finding is corroborated by Berhanu et al. (2020), who reported that WUE of long-term crops increased from 0.23 to 0.90 kg m^{-3}, due to improved soil management practices. Our finding also compares well with reported increase in wheat yield and WUE from 4422 irrigated sites in 22 provinces of China (Yoon and Choi 2020). However, locust and poplar (*Populus tremuloides*) trees had mean WUE of 0.74 kg m^{-3} and 0.67, respectively (Dornbush and von Haden 2017). Therefore, improving WUE in rain-fed agriculture is crucial since there are high demands for food production in China. Water-saving practices have only just begun to be adopted by farmers, and adoption has been poor, which may be ascribed to poor sensitization and extension services (Bhatt et al. 2021). In semi-arid areas, crop improvement programs are aimed at increasing yields (Kong et al. 2020). Therefore, RFRH system is an effective method for low-income farmers to improve rainwater use efficiency in semiarid areas (Wang et al. 2021). In addition, co-application of plastic film mulched RF with biochar may potentially reduce negative effects of plastic film application, such as greenhouse gas emissions and soil residue accumulation (Mak-Mensah et al. 2021a).

Fodder quality is a reflection of essential nutrient elements available to animals for their daily nutrient requirements (Hakl et al. 2017). Thus, suitable fodder quality is critical for high milk and meat production. Fodder quality analysis can help with fodder processing, animal feeding, and nutrition. Optimal fodder quality occurs before plant maturity and seed production (Masikati et al. 2017). Although it is desirable in agricultural production to achieve the highest possible fodder yield, it is also important to have high fodder quality (Sandhu et al. 2020). Crude protein concentration was higher in the leaves than in stems, while ADF and NDF concentrations were higher in stems than in leaves (Hofmann et al. 2019). In this study, CP was high in PF treatments; while FP had the highest mean ADF and NDFs compared to CS and BF ($p < 0.05$). High soil water content in RFRH system decreased fodder stem-leaf ratio, resulting in higher CP content and lower ADF and NDF contents compared to FP. The RFRH system may increase alfalfa fodder quality as plant maturity is delayed, and production of cell wall components is reduced (Sandhu et al. 2020). Drought stress harms fodder quality, accelerating decline in CP content. The RFRH systems, especially PF, increased soil water content and resulted in high CP content and low ADF and NDF contents. Alfalfa and other legumes have distinct leaves and stems, whereas leaf and stems are intertwined in grasses. Leaves contain more digestible nutrients in contrast with stems, which reduces fodder quality in alfalfa (Rezaeian et al. 2020).

Since smallholder farmers often search for alternative methods to increase productivity and reverse land degradation, biodegradable and plastic film mulches could be potential materials for improving yield while increasing provision of other important ecosystem services. A cost–benefit analysis (CBA) was performed to evaluate profitability of application of these materials. The CBA clearly shows varying costs and benefits associated with application of biodegradable and plastic film mulches in alfalfa production over the 5 years. In this study, plastic film mulch yielded the highest cost–benefit ratio compared to FP and CS with no marked difference between them. This is consistent with Ma et al. (2018), who reported positive impact of PF on NEB in spring maize, suggesting that northwestern China could be a maize belt if supported by widespread adoption of PF. Additionally, Ma et al. (2018) noted that use of a biodegradable film may be an option to achieve economic benefit and minimize plastic film pollution. Furthermore, Liu et al. (2020) reported that using 60-cm plastic-mulched ridges increases high crop yield and cost–benefit ratio.

5 Conclusions

Mulch application on semiarid lands can be a viable strategy to strengthen the ridge-furrow rainwater harvesting systems under rain-fed agriculture. Results revealed that integration of ridge-furrow rainwater harvesting and mulching in alfalfa production over the 5 years increased alfalfa fodder yield and quality with higher cost–benefit ratio compared to flat planting. As ridge-furrow rainwater harvesting systems with mulching could be employed for prevention of runoff and soil erosion through allocation of water resources, effective designs should accommodate an adaptive structure for management.

Acknowledgements We would like to thank Dr. John Asekhaen Ohiolei and Dr. Daniel Fiifi Hagan for their technical assistance.

Funding This research was funded by the National Natural Science Foundation of China (42061050 and 41661059).

Declarations

Competing Interests The authors declare no competing interests.

Disclaimer The funders had no role in study design, data collection, analysis, decision to publish, or preparation of the manuscript.

References

Amarasingha RPRK, Suriyagoda LDB, Marambe B, Rathnayake WMUK, Gaydon DS, Galagedara LW, Punyawardena R, Silva GLLP, Nidumolu U, Howden M (2017) Improving water productivity in moisture-limited rice-based cropping systems through incorporation of maize and mungbean: a modelling approach. Agric Water Manag 189:111–122. https://doi.org/10.1016/j.agwat.2017.05.002

Anower MR, Boe A, Auger D, Mott IW, Peel MD, Xu L, Kanchupati P, Wu Y (2017) Comparative drought response in eleven diverse alfalfa accessions. J Agron Crop Sci 203:1–13. https://doi.org/10.1111/jac.12156

AOAC (2005) Official Methods of Analysis of AOAC International. In: 18th (ed) Association of Official Analytical Chemists. AOAC International, Suite 500, 481 North Frederick Avenue Gaithersburg, Mary Land 20877–2417, USA, p 3172

Berhanu T, Beshir W, Lakew A (2020) Effect of integrated technologies on production and productivity of pearl millet in the dryland areas of Wag Himira Administrative Zone, Eastern Amhara, Ethiopia. Int J Agron 2020:1–5. https://doi.org/10.1155/2020/4381870

Bhatt R, Singh P, Hossain A, Timsina J (2021) Rice–wheat system in the northwest Indo-Gangetic plains of South Asia: issues and technological interventions for increasing productivity and sustainability. Paddy Water Environ 19:345–365. https://doi.org/10.1007/s10333-021-00846-7

Caruso G, Stoleru V, De Pascale S, Cozzolino E, Pannico A, Giordano M, Teliban G, Cuciniello A, Rouphael Y (2019) Production, leaf quality and antioxidants of perennial wall rocket as affected by crop cycle and mulching type. Agronomy 9:194. https://doi.org/10.3390/agronomy9040194

Dang J, Liang W, Wang G, Shi P, Wu D (2016) A preliminary study of the effects of plastic film-mulched raised beds on soil temperature and crop performance of early-sown short-season spring maize (*Zea mays L.*) in the North China Plain. Crop J. https://doi.org/10.1016/j.cj.2016.02.002

Dao DA, Kim D, Park J, Kim T (2020) Precipitation threshold for urban flood warning - an analysis using the satellite-based flooded area and radar-gauge composite rainfall data. J Hydro-Environment Res 32:48–61. https://doi.org/10.1016/j.jher.2020.08.001

Das P, Pramanick B, Goswami SB, Maitra S, Ibrahim SM, Laing AM, Hossain A (2021) Innovative land arrangement in combination with irrigation methods improves the crop and water productivity of rice (*Oryza sativa l.*) grown with okra (*abelmoschus esculentus l.*) under raised and sunken bed systems. Agronomy 11:1–13. https://doi.org/10.3390/agronomy11102087

Ding D, Feng H, Zhao Y, Hill RL, Yan H, Chen H, Hou H, Chu X, Liu J, Wang N, Zhang T, Dong Q (2019) Effects of continuous plastic mulching on crop growth in a winter wheat-summer maize rotation system on the Loess Plateau of China. Agric for Meteorol 271:385–397. https://doi.org/10.1016/j.agrformet.2019.03.013

Do HM, Yin KL (2018) Rainfall threshold analysis and Bayesian probability method for landslide initiation based on landslides and rainfall eventS in the past. Open J Geol 08:674–696. https://doi.org/10.4236/ojg.2018.87040

Dornbush ME, von Haden AC (2017) Intensified agroecosystems and their effects on soil biodiversity and soil functions. Elsevier Inc.

Fan T, Wang S, Li Y, Yang X, Li S, Ma M (2019) Film mulched furrow-ridge water harvesting planting improves agronomic productivity and water use efficiency in Rainfed Areas. Agric Water Manag 217:1–10. https://doi.org/10.1016/j.agwat.2019.02.031

Gruffat D, Durand D, Rivaroli D, do Prado IN, Prache S, (2020) Comparison of muscle fatty acid composition and lipid stability in lambs stall-fed or pasture-fed alfalfa with or without sainfoin pellet supplementation. Animal 14:1093–1101. https://doi.org/10.1017/S1751731119002507

Grzegorczyk S, Alberski J, Olszewska M, Grabowski K, Bałuch-Małecka A (2017) Content of calcium and phosphorus and the CA: P ratio in selected species of leguminous and herbaceous plants. J Elem 22:663–669. https://doi.org/10.5601/jelem.2016.21.4.1214

Gu YJ, Han CL, Kong M, Shi XY, Zdruli P, Li FM (2018) Plastic film mulch promotes high alfalfa production with phosphorus-saving and low risk of soil nitrogen loss. F Crop Res 229:44–54. https://doi.org/10.1016/j.fcr.2018.09.011

Gu X, Cai H, Fang H, Li Y, Chen P, Li Y (2020) Effects of degradable film mulching on crop yield and water use efficiency in China: a meta-analysis. Soil Tillage Res 202:.https://doi.org/10.1016/j.still.2020.104676

Guo S, Jiang R, Qu H, Wang Y, Misselbrook T, Gunina A, Kuzyakov Y (2019) Fate and transport of urea-N in a rain-fed ridge-furrow crop system with plastic mulch. Soil Tillage Res 186:214–223. https://doi.org/10.1016/j.still.2018.10.022

Hakl J, Šantrůček J, Pisarčik M, Dindová A (2017) Agronomic factors affecting productivity and nutritive value of perennial fodder crops : a review. 2017:33–41

He H, Wang Z, Guo L, Zheng X, Zhang J, Li W, Fan B (2018) Distribution characteristics of residual film over a cotton field under long-term film mulching and drip irrigation in an oasis agroecosystem. Soil Tillage Res 180:194–203. https://doi.org/10.1016/j.still.2018.03.013

He Z, Zhang T, Liu X, Shang X (2018b) Water-yield relationship responses of maize to ridge-furrow planting systems coupled with multiple irrigation levels in China's Horqin Sandy land. Agronomy 8:.https://doi.org/10.3390/agronomy8100221

Hofmann P, Siegert W, Kenéz Á, Naranjo VD, Rodehutscord M (2019) Very low crude protein and varying glycine concentrations in the diet affect growth performance, characteristics of nitrogen excretion, and the blood metabolome of broiler chickens. J Nutr 149:1122–1132. https://doi.org/10.1093/jn/nxz022

Hu Y, Ma P, Wu S, Sun B, Feng H, Pan X, Zhang B, Chen G, Duan C, Lei Q, Siddique KHM, Liu B (2020) Spatial-temporal distribution of winter wheat (*Triticum aestivum L.*) roots and water use efficiency under ridge–furrow dual mulching. Agric Water Manag 240:106301. https://doi.org/10.1016/j.agwat.2020.106301

Ilstedt U, Bargués Tobella A, Bazié HR, Bayala J, Verbeeten E, Nyberg G, Sanou J, Benegas L, Murdiyarso D, Laudon H, Sheil D, Malmer A (2016) Intermediate tree cover can maximize groundwater recharge in the seasonally dry tropics. Sci Rep 6:1–12. https://doi.org/10.1038/srep21930

Jia Q, Chen K, Chen Y, Ali S, Manzoor SA, Fahad S (2018) Mulch covered ridges affect grain yield of maize through regulating root growth and root-bleeding sap under simulated rainfall conditions. Soil Tillage Res 175:101–111. https://doi.org/10.1016/j.still.2017.08.017

Jia Q, Xu R, Chang S, Zhang C, Liu Y, Shi W, Peng Z, Hou F (2020) Planting practices with nutrient strategies to improves productivity of rain-fed corn and resource use efficiency in semi-arid regions. Agric Water Manag 228:105879. https://doi.org/10.1016/j.agwat.2019.105879

Jin S, Wang Y, Wang X, Bai Y, Shi L (2019) Effect of pruning intensity on soil moisture and water use efficiency in jujube (*Ziziphus jujube Mill.*) plantations in the hilly Loess Plateau Region. China J Arid Land 11:446–460. https://doi.org/10.1007/s40333-019-0129-z

Kader MA, Senge M, Mojid MA, Onishi T, Ito K (2017) Effects of plastic-hole mulching on effective rainfall and readily available soil moisture under soybean (*Glycine max*) cultivation. Paddy Water Environ 15:659–668. https://doi.org/10.1007/s10333-017-0585-z

Kong M, Jia Y, Gu YJ, Han CL, Song X, Shi XY, Siddique KHM, Zdruli P, Zhang F, Li FM (2020) How film mulch increases the corn yield by improving the soil moisture and temperature in the early growing period in a cool, Semi-Arid Area. Agronomy 10:.https://doi.org/10.3390/agronomy10081195

Li C, Wang C, Wen X, Qin X, Liu Y, Han J, Li Y, Liao Y, Wu W (2017) Ridge–furrow with plastic film mulching practice improves maize productivity and resource use efficiency under the wheat–maize double–cropping system in dry semi–humid areas. F Crop Res 203:201–211. https://doi.org/10.1016/j.fcr.2016.12.029

Li W, Wen X, Han J, Liu Y, Wu W, Liao Y (2017) Optimum ridge-to-furrow ratio in ridge-furrow mulching systems for improving water conservation in maize (*Zea may L.*) production.

Environ Sci Pollut Res 24:23168–23179. https://doi.org/10.1007/s11356-017-9955-8

Li Y, Su D (2017) Alfalfa water use and yield under different sprinkler irrigation regimes in North arid regions of China. Sustain 9:.https://doi.org/10.3390/su9081380

Li H, Shen H, Wang Y, Wang Y, Gao Q (2021) Effects of ridge tillage and straw returning on runoff and soil loss under simulated rainfall in the mollisol region of northeast china. Sustain 13:.https://doi.org/10.3390/su131910614

Liu G, Zuo Y, Zhang Q, Yang L, Zhao E, Liang L, Tong YA (2018) Ridge-furrow with plastic film and straw mulch increases water availability and wheat production on the Loess Plateau. Sci Rep. https://doi.org/10.1038/s41598-018-24864-4

Liu Y, Wu Q, Ge G, Han G, Jia Y (2018) Influence of drought stress on afalfa yields and nutritional composition. BMC Plant Biol 18:1–23. https://doi.org/10.1186/s12870-017-1226-9

Liu X, Wang Y, Yan X, Hou H, Liu P, Cai T, Zhang P, Jia Z, Ren X, Chen X (2020) Appropriate ridge-furrow ratio can enhance crop production and resource use efficiency by improving soil moisture and thermal condition in a semi-arid region. Agric Water Manag 240:106289. https://doi.org/10.1016/j.agwat.2020.106289

Luo CL, Zhang XF, Duan HX, Zhou R, Mo F, Mburu DM, Wang BZ, Wang W, Kavagi L, Xiong YC (2021) Responses of rainfed wheat productivity to varying ridge-furrow size and ratio in semiarid eastern African Plateau. Agric Water Manag 249:106813. https://doi.org/10.1016/j.agwat.2021.106813

Ma D, Chen L, Qu H, Wang Y, Misselbrook T, Jiang R (2018) Impacts of plastic film mulching on crop yields, soil water, nitrate, and organic carbon in northwestern China: a meta-analysis. Agric Water Manag 202:166–173. https://doi.org/10.1016/j.agwat.2018.02.001

Mak-Mensah E, Obour PB, Essel E, Wang Q, Ahiakpa JK (2021) Influence of plastic film mulch with biochar application on crop yield, evapotranspiration, and water use efficiency in northern China: a meta-analysis. PeerJ 9:e10967. https://doi.org/10.7717/peerj.10967

Mak-Mensah E, Obour PB, Wang Q (2021) Influence of tied-ridge-furrow with inorganic fertilizer on grain yield across semiarid regions of Asia and Africa: a meta-analysis. PeerJ 9:e11904. https://doi.org/10.7717/peerj.11904

Mak-Mensah E, Sam FE, Safnat Kaito IOI, Zhao W, Zhang D, Zhou X, Wang X, Zhao X, Wang Q (2021) Influence of tied-ridge with biochar amendment on runoff, sediment losses, and alfalfa yield in northwestern China. PeerJ 9:e11889. https://doi.org/10.7717/peerj.11889

Marí AI, Pardo G, Cirujeda A, Martínez Y (2019) Economic evaluation of biodegradable plastic films and paper mulches used in open-air grown pepper (*capsicum annum l.*) crop. Agronomy 9:. https://doi.org/10.3390/agronomy9010036

Masikati P, Homann Kee-Tui S, Descheemaeker K, Sisito G, Senda T, Crespo O, Nhamo N (2017) Integrated assessment of crop-livestock production systems beyond biophysical methods: role of systems simulation models. In: Smart Technologies for Sustainable Smallholder Agriculture: Upscaling in Developing Countries

Milkias A, Tadesse T, Zeleke H (2018) Evaluating the effects of in-situ rainwater harvesting techniques on soil moisture conservation and grain yield of maize (*Zea mays L.*) in Fedis District, Eastern Hararghe, Ethiopia. Turkish J Agric - Food Sci Technol 6:1129. https://doi.org/10.24925/turjaf.v6i9.1129-1133.1839

Mo F, Wang J-Y, Xiong Y-C, Nguluu SN, Li F-M (2016) Ridge-furrow mulching system in semiarid Kenya: a promising solution to improve soil water availability and maize productivity. Eur J Agron 80:124–136. https://doi.org/10.1016/j.eja.2016.07.005

Mo F, Wang JY, Li FM, Nguluu SN, Ren HX, Zhou H, Zhang J, Kariuki CW, Gicheru P, Kavagi L, Cheruiyot WK, Xiong YC (2017) Yield-phenology relations and water use efficiency of maize (*Zea mays L.*) in ridge-furrow mulching system in semiarid east African Plateau/631/61/631/158/9/30 article. Sci Rep 7:1–14. https://doi.org/10.1038/s41598-017-03372-x

Rai RK, Singh VP, Upadhyay A (2017) Irrigation scheduling. In: Planning and Evaluation of Irrigation Projects. Elsevier, pp 385–412

Rezaeian M, Tohidi Moghadam M, Kiaei MM, Mahmuod Zadeh H (2020) The effect of heavy metals on the nutritional value of Alfalfa: comparison of nutrients and heavy metals of Alfalfa (*Medicago sativa*) in industrial and non-industrial areas. Toxicol Res 36:183–193. https://doi.org/10.1007/s43188-019-00012-6

Rodrigues JPP, Ramin M, Huhtanen P, Aru F, Detmann E, Marcondes MI (2018) Effect of soya bean oil supplementation and forage type on methane production and fibre digestibility using the in vitro gas production system. Grass Forage Sci 73:368–380. https://doi.org/10.1111/gfs.12326

Sandhu A, Dhaliwal SS, Shukla AK, Sharma V, Singh R (2020) Fodder quality improvement and enrichment of oats with Cu through biofortification: a technique to reduce animal malnutrition. J Plant Nutr 43:1378–1389. https://doi.org/10.1080/01904167.2020.1739291

Sebnie W, Mengesha M, Girmay G, Feyisa T, Asgedom B, Beza G, Dejene D (2020) Evaluation of micro-dosing fertilizer application on sorghum (*Sorghum bicholor L*) production at Wag-Lasta Areas of Amhara Region, Ethiopia. Sci Rep 10:6–11. https://doi.org/10.1038/s41598-020-63851-6

Sekara A, Pokluda R, Cozzolino E, del Piano L, Cuciniello A, Caruso G (2019) Plant growth, yield, and fruit quality of tomato affected by biodegradable and non-degradable mulches. Hortic Sci 46:138–145. https://doi.org/10.17221/218/2017-HORTSCI

Sun L, Huang Z, Cui Z, Lu R, Zhang RQ, Liu Y, López-Vicente M, Ahirwal J, Wei XH, Wu GL (2018) Soil water depletion in planted alfalfa pastures in an alpine pastoral area. Water (Switzerland) 10:.https://doi.org/10.3390/w10111538

Verheijen FGA, Zhuravel A, Silva FC, Amaro A, Ben-Hur M, Keizer JJ (2019) The influence of biochar particle size and concentration on bulk density and maximum water holding capacity of sandy vs sandy loam soil in a column experiment. Geoderma 347:194–202. https://doi.org/10.1016/j.geoderma.2019.03.044

Wang D, Wang L (2018) Soil water dynamics in apple orchards of different ages on the loess plateau of China. Vadose Zo J 17:180049. https://doi.org/10.2136/vzj2018.03.0049

Wang Q, Zhang D, Zhou X, Liu J, Liu Q, Li X, Sample DJ, Zhang Y, Zhang R (2019) Comparing yield, quality, water use efficiency, and value between fodder and grain produced using ridge-furrow rainwater harvesting in a semiarid region. Crop Sci 59:2214–2226. https://doi.org/10.2135/cropsci2019.03.0180

Wang JY, Mo F, Zhou H, Kavagi L, Nguluu SN, Xiong YC (2021) Ridge–furrow with grass straw mulching farming system to boost rainfed wheat productivity and water use efficiency in semiarid Kenya. J Sci Food Agric 101:3030–3040. https://doi.org/10.1002/jsfa.10937

Xin X, Sun Z, Xiao J, Feng L, Yang N, Liu Y (2021) Ridge-furrow rainfall harvesting planting and its effect on soil erosion and soil quality in sloping farmland. Agron J 113:863–877. https://doi.org/10.1002/agj2.20527

Yang W, Feng G, Miles D, Gao L, Jia Y, Li C, Qu Z (2020) Impact of biochar on greenhouse gas emissions and soil carbon sequestration in corn grown under drip irrigation with mulching. Sci Total Environ 729:138752. https://doi.org/10.1016/j.scitotenv.2020.138752

Yoon PR, Choi JY (2020) Effects of shift in growing season due to climate change on rice yield and crop water requirements. Paddy Water Environ 18:291–307. https://doi.org/10.1007/s10333-019-00782-7

Zhang K, Xing Y, Wang G, Shemi R, Duan M, Wang L, Xie X (2019) Ridge-furrow with film mulching practice ameliorates soil microbial metabolic activity and carbon utilization in rhizosphere soil of rapeseed (*Brassica napus L.*). J Soils Sediments 19:2764–2776. https://doi.org/10.1007/s11368-019-02243-4

Zhang G, Mo F, Shah F, Meng W, Liao Y, Han J (2021) Ridge-furrow configuration significantly improves soil water availability, crop water use efficiency, and grain yield in dryland agroecosystems of the Loess Plateau. Agric Water Manag 245:106657. https://doi.org/10.1016/j.agwat.2020.106657

Zhao Y, Zhai X, Wang Z, Li H, Jiang R, Lee Hill R, Si B, Hao F (2018) Simulation of soil water and heat flow in ridge cultivation with plastic film mulching system on the Chinese Loess Plateau. Agric Water Manag 202:.https://doi.org/10.1016/j.agwat.2018.02.017