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Effects of ridge-furrow rainwater-harvesting with biochar application on sediment control and alfalfa (*Medicago sativa* L.) fodder yield increase in semiarid regions of China

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Abstract

Purpose Drought and soil erosion are significant environmental challenges to agricultural production in the Loess Plateau of China. We hypothesized that ridge-furrow rainwater-harvesting, especially tied-ridge-furrow rainwater-harvesting, with biochar application would increase soil moisture, temperature, and alfalfa fodder yield, and reduce runoff and sediment yield.

Materials and methods A split-plot design experiment was conducted to determine the effects of biochar application patterns (biochar application pattern and no biochar application pattern) and tillage practices (tied-ridging, open-ridging, and flat-planting) on soil temperature, moisture, runoff, sediment yield, fodder yield, and water use efficiency (WUE) of alfalfa during two consecutive alfalfa-growing years: 2019 and 2020.

Results Biochar application decreased runoff, sediment yield, soil temperature, and increased soil water storage, compared to no biochar application. Open-ridging and tied-ridging significantly increased soil water storage, fodder yield, WUE of alfalfa, and decreased runoff and sediment yield, compared to flat-planting. Compared to no biochar application, soil water storage for biochar application increased by 34.51 mm during alfalfa growing season over two years. The mean runoff and sediment yield for no biochar application were 1.48–1.69 and 1.94–2.25 times greater than that for biochar application, respectively. Compared to flat-planting, the mean decrease of runoff and sediment yield was 27.4–31.9% and 60.1–64.7%, respectively, for open-ridging, while it was 37.1–55.2% and 71.8–82.4% for tied-ridging. The mean increase of soil water storage, fodder yield, and WUE of alfalfa for open-ridging was 39.5–52.1 mm, 26.2–31.7%, and 10.07–14.86 kg ha^{-1} mm^{-1}, respectively, while it for tied-ridging was 31.2–60.5 mm, 26.5–35.2%, and 12.14–16.55 kg ha^{-1} mm^{-1} over two years.

Conclusions Tied-ridge-furrow rainwater-harvesting with biochar application is a potentially effective adaptation technology that could control soil erosion and increase alfalfa fodder yield in semiarid regions.

Keywords Biochar amendment · Conservation technology · Moisture conservation · Soil erosion · Fodder yield

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Abbreviations

RFRH	Ridge-furrow rainwater-harvesting
TRFRH	Tied-ridge-furrow rainwater-harvesting
WUE	Water use efficiency
NFY	Net fodder yield
AFY	Actual fodder yield

1 Introduction

Drought, soil erosion, and erratic rainfall are negative environmental hazards for the sustainability of agricultural production and environmental development in arid and semiarid regions (Wang et al. 2013b; Fang et al. 2016). In the Loess Plateau of China, climate change, environmental degradation, and inappropriate agricultural practices generally have increased the risk of drought and soil erosion (Gupta et al. 2020; Wang et al. 2021a). The annual mean pan evaporation (1535 mm) is much greater than the average annual precipitation (386 mm) in this area (Zhang et al. 2020b). The annual precipitation mainly occurs in short-term high-intensity rainstorms, which easily block surface soil pores and generate soil crust, and reducing infiltration rate (Wang et al. 2018). As rainfall intensity exceeds infiltration rate, the rainfall generates runoff flowing along soil surface into adjacent low-lying areas. Runoff is the direct cause of soil erosion by detaching and dislodging soil particles from soil aggregate or crust on sloping land (Liu et al. 2020; Zhao et al. 2021). Consequently, the fragmented soil aggregate structure decreases soil moisture and nutrient retention, resulting in land productivity decline (Hossain et al. 2020). Long-term soil erosion has shaped a large number of sloping lands and criss-cross networks of ravines, which increased soil susceptibility to runoff and erosion (Wang et al. 2011). Soil nutrients are washed away from farmland with runoff and sediment, leading to soil fertility decline and agricultural land degradation (Mailapalli and Thompson 2011; Wang et al. 2018). To combat runoff and sediment generation, and to increase soil moisture and crop yield on sloping lands, it is necessary to adopt appropriate land management measures and soil and water conservation technologies which improve rainwater infiltration and hindering overland flow on sloping land (Xin et al. 2021).

Ridge-furrow rainwater-harvesting (RFRH) has been widely adopted as a promising and pragmatic practice in handling drought risk and controlling soil erosion in arid and semi-arid regions (Meng et al. 2020). In these regions, an innovative pattern of RFRH, tied-ridge-furrow rainwater-harvesting (TRFRH), has been designed to lengthen runoff retention time and facilitate infiltration time (Hu and Stroosnijder 2010). In TRFRH, rainwater-harvesting-ridges, tied-ridges, and furrows form a series of small basins, which can reduce runoff and increase available water for crop production (Mesfin et al. 2009). However, TRFRH could lead to waterlogging, ridge overtopping, ridge failure, and crop failure if it was not properly designed (Wang et al. 2018). Although field trials have focused on reducing runoff and controlling sediment in planting trees and other dibbling crops in Africa (Nyamangara and Nyagumbo 2010), few field trials have been conducted on seeding crops in the Loess Plateau of China, especially for alfalfa.

Biochar is a novel carbon-rich material manufactured from plant residue or animal waste through controlled thermal-chemical pyrolysis temperature and anoxic conditions (Hou et al. 2020). Biochar is characterized by multiple porous structure, large specific surface area, and strong soil water holding capacity (Fu et al. 2021). As a soil additive modifier, biochar had positive effects on improving soil porosity, aeration, infiltration rate, soil water retention, and nutrient retention, thus reducing soil bulk density, surface runoff, and soil erosion (Obia et al. 2017; He et al. 2018; Zhang et al. 2020a). During high rainfall events, biochar application could prevent runoff generation and improve crop yield (Zhang et al. 2015; Feng et al. 2021; Wei et al. 2020). Nevertheless, some researchers have reported that biochar application did not reduce soil erosion on a hillslope because the soil amended with biochar had loose connections and weak bonds between soil particles, and was susceptible to runoff and soil erosion (Major et al. 2010; Wang et al. 2013a). Fister et al. (2013) found that biochar spreading on the soil surface increased soil susceptibility to runoff and soil erosion, especially during the first rainfall event following the biochar application. Biochar addition to soil decreased runoff and sediment yield under low application rates (1% and 3% weight), while promoted runoff and sediment yield under high application rates (5% and 7% weight) on sloping land (Li et al. 2019). Zhang et al. (2019b) found that the soil amended with biochar decreased runoff by 2.4–10.8% and increased sediment yield by 20.8–50.8%, compared to no biochar application. The performance of biochar amendment to soil on runoff, soil moisture, sediment, and crop yield strongly depends on biochar type, particle size, application rate, crop type, soil type, tillage practice, and climatic condition (Li et al. 2019; Zhang et al. 2021). Consequently, it is highly necessary to investigate the mechanism of RFRH with biochar application on soil erosion and crop yield in the Loess Plateau of China.

Alfalfa (*Medicago sativa* L.) is a perennial legume forage widely cultivated in the Loess Plateau of China (Zhang et al. 2017). Alfalfa has several unique valuable properties and advantages which would enable the crop to be high drought resistant (Ge et al. 2020a). Alfalfa's deep root system enhances soil cohesion, creates channels, improves soil stability and infiltration rate, and effectively controls soil erosion (Guo et al. 2019). Alfalfa's high canopy protects soil against raindrop impact, intercepts rainfall, reduces both runoff and velocity, allows improved infiltration capacity, and increases water intake and soil water storage (Wang et al. 2018). Alfalfa plots decreased runoff coefficient and sediment yield by 28.3% and 78.4%, respectively, and increased infiltration rate by 1.77 times greater, compared to bare-soil plots (Wu et al. 2011). However, alfalfa utilizes high amounts of soil water in deep soil profile, and this leads to soil desiccation in arid and semiarid regions (Chen et al. 2021). Therefore, it is critical to develop an effective tillage practice to control soil erosion, maintain crop yield, and avoid over-utilization of soil water.

Limited research is available on the effects of RFRH with biochar application on soil erosion and crop yield. We hypothesized that RFRH, especially TRFRH, with biochar application would increase soil moisture, temperature, alfalfa fodder yield, and decrease sediment and runoff (Fig. 1). The objective of this study was to select biochar application pattern and tillage practice in the RFRH to reduce soil erosion and increase crop yield under natural rainfall condition.

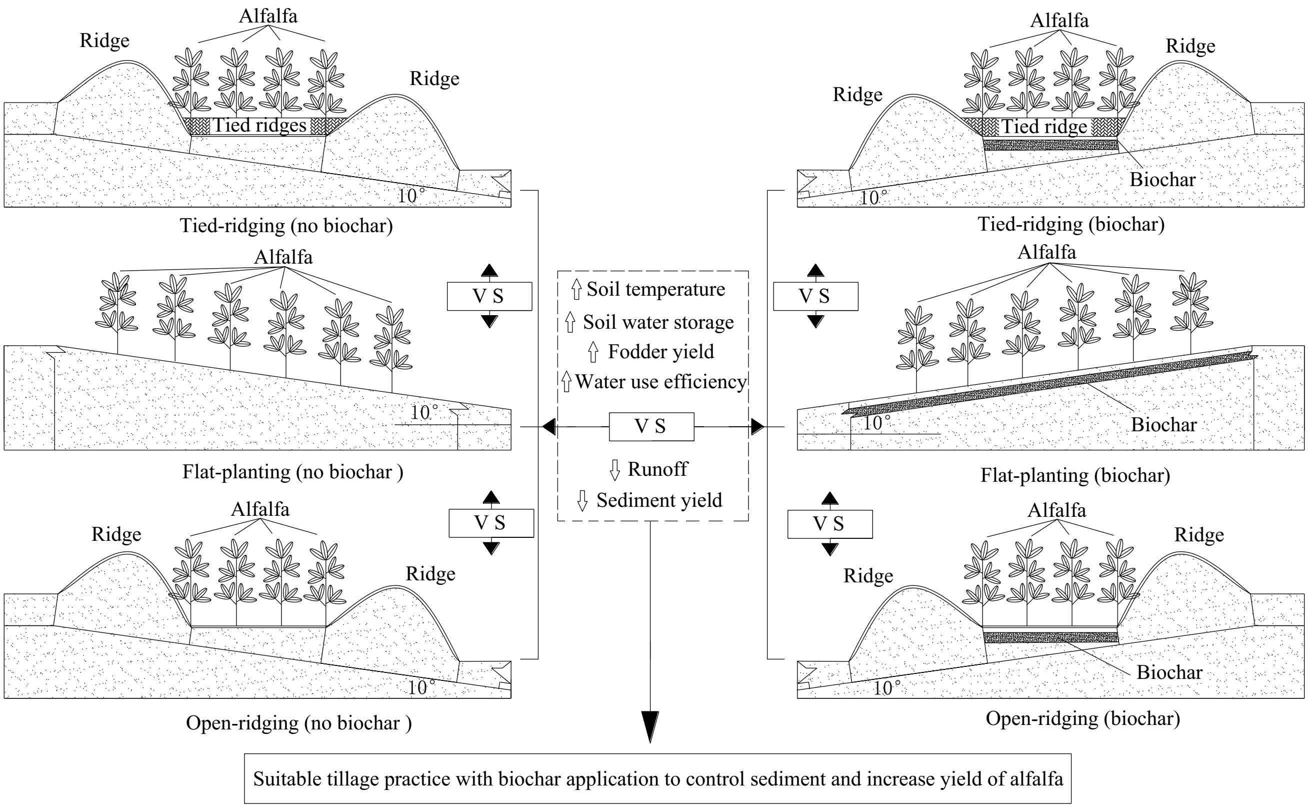

Fig. 1 Hypothesized schematic on alfalfa production in ridge-furrow rainwater-harvesting with biochar application on sloping land

2 Materials and methods

2.1 The experimental site description

A field experiment was conducted at the Anjiapo experimental site (latitude of 35° 35′ N, longitude of 104° 39′ E, and altitude of 2076 m above sea level) of Dingxi Institute of Soil and Water Conservation during two consecutive alfalfa-growing years: 2019 and 2020. The experimental site is located at Anjiapo catchment area in Fengxiang town, Anding district, Dingxi, Gansu province, China (Fig. 2). The experimental station is a typically semiarid

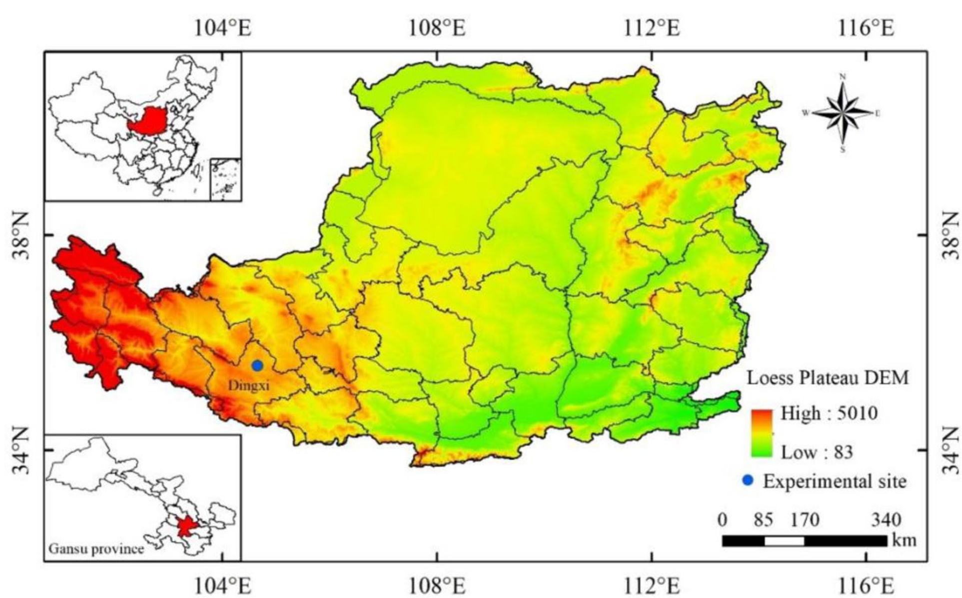

Fig. 2 The geographical location of the experimental site in the Loess Plateau of China

Table 1 Soil chemical properties in the experimental field

Soil depth (cm)	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Total K ($g\ kg^{-1}$)	Organic matter ($g\ kg^{-1}$)	Ammonium N ($mg\ kg^{-1}$)	Olsen P ($mg\ kg^{-1}$)	Available K ($mg\ kg^{-1}$)	pH
0–20	0.62	0.76	20.7	9.56	65.7	7.78	135	7.83
20–40	0.54	0.64	20.51	7.68	22.1	3.17	90	7.82

medium temperate area on the Loess Plateau. The most common topography of this area is ravines, mountains, and hills. Farming lands always have slight slopes. According to the 50 years (1970–2020) mean record from the Dingxi Meteorological Station, mean annual air temperature was 6.7 °C, and mean annual precipitation was 392 mm with approximately 76% of precipitation falling during alfalfa growing season (April-September). Potential annual evaporation was about 1445 mm. Annual sunshine duration reached 2438 h, and frost-free period was about 140–160 days. Mean air humidity was approximately 65.8%. The soil in the experimental site is loess-like loam developed from wind-accumulated loess with weak erosion resistance. The type of soil is classified as a calcic Cambisol according to the American soil classification system (Chen et al. 2021). Soil bulk density ranges from 1.09 to 1.36 g cm^{-3} within 2 m depth, and field water holding capacity ranges from 20 to 23%. Permanent wilting point is 5.16%. The chemical properties of soil (0–40 cm layer) are presented in Table 1. These properties were measured before the experiment. The farming practice was monoculture with once crop harvesting in a year because of the lack of heat and low temperature. The major cultivated crops in this region are spring wheat (*Triticum aestivum* L.), potato (*Solanum tuberosum* L.), maize (*Zea mays* L.), and flax (*Linum usitattssimum* L.). The major forage crops are alfalfa (*Medicago sativa* L.) and sainfoin (*Onobrychis vichfolia* L. *Scop.*).

2.2 Rainfall

Mean monthly precipitation compared to the 50-year (1971–2020) mean records in 2019 and 2020 is presented in Fig. 3. The annual precipitation was 520.8 mm in 2019 and 512.5 mm in 2020. These two years were wetter than the normal year, as the 50-year mean annual precipitation is 395.6 mm. Approximately 65–70% of the rainfall events was less than 5 mm, which was too small to be utilized by crops in flat-planting. The monthly rainfall was 2.5, 11.6, 8.8, 24.3, 49, 88.2, 115.2, 109.1, 52.7, 49.8, 9.1, and 0.5 mm, respectively, from January to December in 2019, while it was 7.5, 4.7, 13.4, 15, 75, 80.5, 91.2, 138.2, 44.8, 28.2, 10.2, and 3.8 mm from January to December in 2020. Precipitation during alfalfa growing season (from April 1 to October 15) was 488.3 mm in 2019 and 472.9 mm in 2020.

2.3 Biochar

Rice straw was used as a feedstock in biochar production through pyrolysis at approximately 500–700 °C in partial absence of oxygen in a programmable tube furnace at the Engineering Research Center of Biochar of Zhejiang Province. The biochar mass was ground to pass through a 2-mm sieve to obtain a fine granular consistency that would be mixed uniformly into soil. The physical and chemical properties of the biochar are summarized in Table 2.

2.4 Experimental design

A split-plot design was used in this experiment with biochar application pattern as the main plot and tillage practice as the sub-plot, and alfalfa was used as an indicator crop. The two biochar application patterns were biochar application (application rate was 3×10^4 kg ha^{-1}) and no biochar application, respectively. The three tillage practices were tied-ridging, open-ridging, and flat-planting,

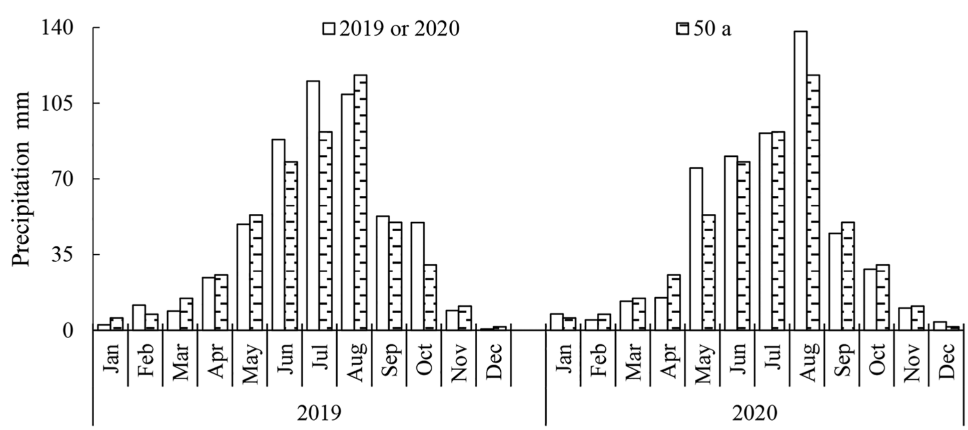

Fig. 3 Mean monthly precipitation compared with the mean 50-year records (1971–2020) at the experimental site in 2019 and 2020

Table 2 Biochar physical and chemical properties

Items	Total N ($g\ kg^{-1}$)	Total P ($g\ kg^{-1}$)	Total K ($g\ kg^{-1}$)	OC ($g\ kg^{-1}$)	C (%)	PH /	Porosity (μm)	BD ($g\ cm^{-3}$)	SSA ($m^2\ g^{-1}$)	Ash (%)
Values	4.56	1.95	27.35	474.8	32.58	8.08	21.4	0.17	1.05	34.8

OC organic carbon, *BD* bulk density, *SSA* specific surface area

respectively. There were six treatments (two biochar application patterns × three tillage practices) with three replications. According to local farming experience, rainwater-harvesting-ridges and tied-ridges were arched with manual labour. The width and height of rainwater-harvesting-ridges was 45 and 15–20 cm, respectively. The width and height of tied-ridges were 15–20 and 10–15 cm, respectively. Rainwater-harvesting-ridges were mulched with 0.008 mm thickness of biodegradable film, and tied-ridges were compacted manually with soil. The compacted soil on tied-ridges became soil crust after rainfalls. The interval distance between two no-staggered tied ridges was 2.5 m. The 60 cm wide furrow was used for sowing alfalfa. A profile diagram of treatments is presented in Fig. 4.

Each plot's total area is 50 m^2 (10 m length × 5 m width). For tied-ridging and open-ridging plot, there were nine ridges and 10 furrows, and actual planting area was 30 m^2 (5 m length × 0.6 m width × 10 furrows) with 40 rows of alfalfa. For each flat-planting plot, actual planting area was 50 m^2 with 66 rows of alfalfa. Concrete bricks were remained 15 cm above ground and buried 10 cm into soil, and were built around plots to collect runoff and sediment from the plot, as well as to prevent runoff and sediment from adjacent areas. A gutter was built at the upside of each plot to intercept runoff and sediment from outside. Another gutter was built at the downside of each plot to convey runoff and sediment into a sedimentation pond. The sedimentation pond was built with concrete bricks to prevent infiltration. The sedimentation pond volume is 2.25 m^3 (1.5 m length × 1.5 m width × 1.5 m depth) (Fig. 4).

2.5 Field management

Suitable farmland with slopes of 10° was chosen at Anjiapo Catchment area for the trial field. Once soil was thawed completely, the field was laid out after removing litter layer and debris on field surface. A 20-30cm deep soil surface layer was manually shoveled and piled up. Plots were built in accurate sizes and slope using a tape measure and slope meter on April 1, 2019. Plot boundaries and the sedimentation ponds were built on April 12, 2019. The furrows were leveled, ploughed, and harrowed once before sowing. For biochar application, biochar was spread evenly over furrows and then ploughed into 20–30 cm depth soil before sowing on April 10, 2019. The piled-up soil surface layer was spread evenly on furrow surface in RFRH or all surface areas in flat-planting. The procedure of rainwater-harvesting-ridges mulching was done on April 5, 2019, and March 25, 2020. Tied-ridges were manually built around two months after

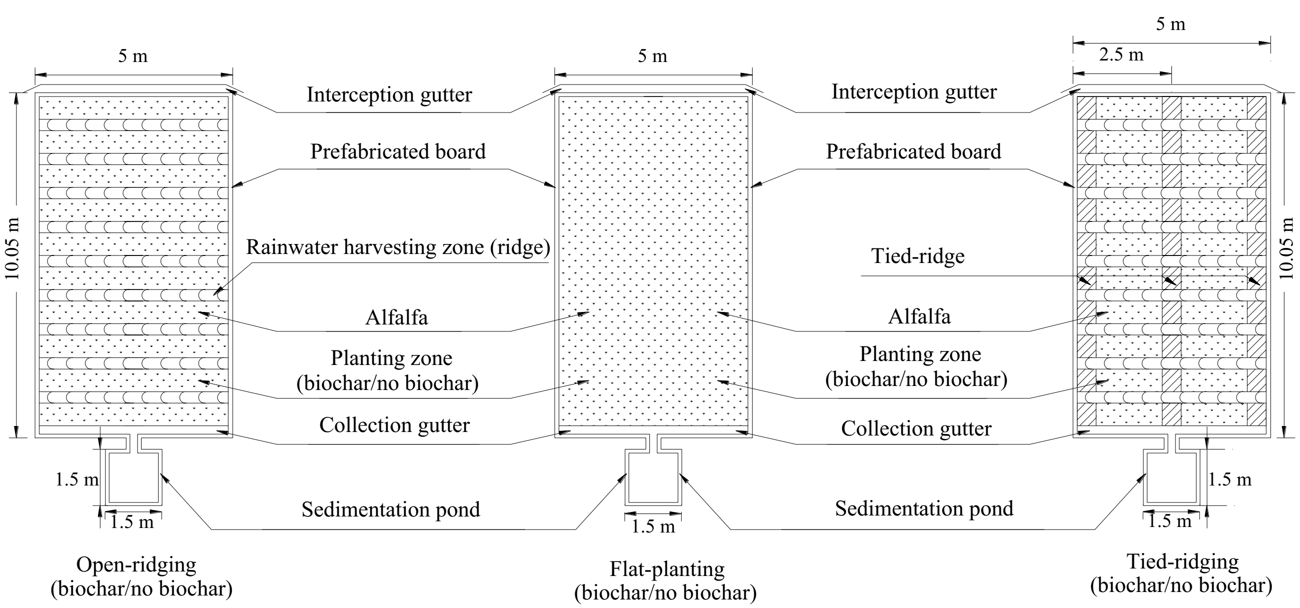

Fig. 4 Diagram of field layout for alfalfa production in ridge-furrow rainwater-harvesting with biochar application

sowing. The trial plots were fenced with 1.5 m high iron mesh to prevent wildlife intruding, trampling, and damaging to alfalfa and ridges.

Local alfalfa cultivar (No 3 Gannong) was sown at a seed rate of 22.5 kg ha^{-1} on April 12, 2019. Four rows were sown in a 60 cm wide furrow in 2–3 cm depth with 15 cm width space between two rows. The sowing rate was the relative same based on furrow areas in RFRH and all plot surfaces in flat-planting. Weeds were manually done according to weed growing status, and no fertilizer or irrigation was carried during two alfalfa-growing years.

2.6 Sampling and measurements

2.6.1 Rainfall

The precipitation was measured using meteorological instruments at the meteorological station. The meteorological station is 30–50 m away from the trial field.

2.6.2 Soil temperature

Mercury-in-glass geothermometers with bent stems were buried at furrow bottoms at soil depths of 5, 10, 15, 20, and 25 cm. Soil temperature was measured at five days intervals from sowing or green up to the last harvesting. The mean daily soil temperature was calculated by determining the mean of three daily recordings around 8:00 a.m., 2:00 p.m., and 6:00 p.m.

2.6.3 Soil moisture

During alfalfa growing season, soil moisture was measured by the oven-drying method at 30-day intervals approximately. The soil sample depth was divided into 11 layers, which were 0–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, and 180–200 cm, respectively.

2.6.4 Runoff and sediment

The runoff and sediment were measured 24 h after each rainfall to reduce evaporation and leakage. The water depth was measured randomly at five locations by a steel ruler.

The sediment in the collection gutter was cleaned and collected into the sedimentation pond with a broom and spade. The runoff was stirred up with a broom and spade continuously for 10–15 min until the runoff turbidity was uniform in the sedimentation pond. The turbid runoff was sampled immediately with three 1000 ml measuring flasks. The samples were clarified, filtered, dried, and weighted to get sediment yield. The sedimentation ponds were emptied and cleaned by pumping for the next runoff and sediment collection.

2.6.5 Alfalfa fodder yield

At initial flowering stage and senescence, alfalfa was manually harvested twice (29 August and 19 October) in 2019 and three times (28 June, 28 August, and 15 October) in 2020 with sickles. The freshly harvested alfalfa was weighed immediately after harvesting. About 5–6 kg sample was taken from the freshly harvested alfalfa and was dried in an oven at 105 °C for one h and then at 75 °C until a constant weight was reached.

2.6.6 Calculation

Soil water storage was calculated using the following formulae.

$$W = \sum_{i=1}^{10} \theta_i \times BD_i \times H \times 10 \quad (1)$$

where θ is soil water content (%), BD is bulk density (g cm^{-3}), H is soil layer thickness (cm).

Runoff, sediment loss, and runoff coefficient were calculated using the following formulae.

$$V_{rf} = A_{pl} \times D_{pl} \quad (2)$$

$$W_{st} = V_{rf} \times \frac{W_{se\ st}}{V_{se}} \quad (3)$$

$$D_{rf} = \frac{V_{rf}}{A_{pt}} \quad (4)$$

$$W_{stpa} = \frac{\mathrm{W}_{st}}{A_{pt}} \quad (5)$$

$$RE = \frac{V_{rf}}{P \times A_{pt}} \quad (6)$$

where V_{rf} (m^3) is runoff volume in the sedimentation pond, A_{pl} (2.25 m^2) is the inner basal area of the sedimentation pond, D_{pl} (m) is runoff depth in the sedimentation pond, W_{st} (g) is sediment weight collected in the sedimentation pond, V_{se} (L) is sample volume, $W_{\mathrm{se\ st}}$ (g) is the sediment weight of the sample, D_{rf} (L m^{-2}) is runoff depth, A_{pt} (m^2) is the projection area of each plot, $W_{\mathrm{st\ pa}}$ (g m^{-2}) is the sediment weight per area, RE (%) is runoff coefficient, P (mm) is precipitation.

The total actual evapotranspiration (ET, mm) during alfalfa growing season and WUE (kg ha^{-1} mm^{-1}) of alfalfa were calculated using the following formulas (Li and Gong 2002):

Tied ridging and open ridging:

$$\mathrm{ET} = \mathrm{P} + \mathrm{Re} \times \mathrm{P} \times \frac{h_1}{h_2} + \left(W_1 - W_2\right) \tag{7}$$

$$\mathrm{WUE} = \frac{NFY}{\mathrm{ET}} \tag{8}$$

Flat-planting:

$$\mathrm{ET} = \mathrm{P} + (W_1 - W_2) \tag{9}$$

$$\mathrm{WUE} = \frac{NFY}{\mathrm{ET}} = \frac{AFY}{\mathrm{ET}} \tag{10}$$

where P (mm) is the cumulative precipitation of alfalfa growing season, Re (%) is average annual runoff coefficient (Wang et al. 2018), h_1 is ridge width (45 cm), h_2 is furrow width (60 cm), W_1 (mm) and W_2 (mm) are the amounts of soil water storage in 0-200 cm depth measured one day before sowing or green up and one day after the last harvesting. Alfalfa fodder yield was calculated by two approaches. Net fodder yield (NFY) was fodder yield based on furrow areas (exclude ridge and tied-ridge areas). Actual fodder yield (AFY) was fodder yield based on whole land areas of ridges (include ridges and tied-ridges) and furrows. The percolation and net recharge from groundwater are assumed to be negligible in this region (Zhao et al. 2012).

2.6.7 Statistical analysis

The main effects of treatments and year, and the interaction effects between treatments and year, were determined using univariate ANOVA (analysis of variance) with the General Linear Models procedure. SPSS Statistics 20.0 and Excel 365 software were used for data processing, statistics program, graphing, and tabulation.

3 Results

3.1 Soil temperature

The topsoil temperature at furrow bottoms during alfalfa growing season is presented in Fig. 5. The topsoil temperature gradually increased as air temperature increased from early spring to early summer and kept a small fluctuation during summer; while it decreased as air temperature decreased from late summer to autumn in both years. Compared to flat-planting, during alfalfa growing season, in 2019, the mean topsoil temperature at furrow bottoms for open-ridging and tied-ridging decreased by 0.64 ℃ and 1.26 ℃, respectively, under biochar application, while it decreased by 0.86 ℃ and 1.54 ℃ under no biochar application. In 2020, the mean topsoil temperature at furrow bottoms for open-ridging and tied-ridging decreased by 0.76 ℃ and 1.22 ℃, respectively, under biochar application, while it was decreased by 0.51 ℃ and 1.11 ℃ under no biochar application. Compared to no biochar application, the mean topsoil temperature at furrow bottoms decreased by 0.53 ℃ in 2019 and 1.07 ℃ in 2020 for biochar application.

3.2 Soil water storage

Soil water storage during alfalfa growing season in 2019 and 2020 is presented in Fig. 6. The soil water storage increased firstly from April to May, then decreased from May to July, and finally increased from July to October. In two years, soil water storage in down-slope was higher than that in middle-slope, which was higher than that in up-slope. In most cases, the soil water storage in tied-ridging was significantly higher than that in open-ridging, which was significantly higher than that in flat-planting. The soil water storage for biochar application was clearly higher than that for no biochar application. Compared to flat-planting, during the alfalfa growing season, in 2019, the mean soil water storage for open-ridging and tied-ridging increased by 45.22 and 72.83 mm, respectively, under biochar application, while it increased by 11.24 and 54.22 mm under no biochar application. In 2020, the mean soil water storage for open-ridging and tied-ridging increased by 59.03 and 48.17 mm, respectively, under biochar application, while it increased by 67.77 and 8.27 mm under no biochar application. Compared to no biochar application, the mean soil water storage for biochar application increased by 42.93 mm in 2019 and 26.09 mm in 2020.

3.3 Runoff, sediment, and runoff coefficient

The statistical analysis results showed that the main effect of biochar application, tillage practice, and year on runoff, sediment yield, AFY and WUE was significant ($P < 0.05$) (Table 3). The interaction effect between biochar application and tillage practice, between biochar application and year, between tillage practice and year were statistically significant in runoff, sediment yield, and WUE, but not significant in AFY. The interaction effect between biochar application, tillage practice, and year was statistically significant in runoff, but not significant in sediment yield, AFY, and WUE.

Runoff is a crucial indicator for evaluating soil moisture and soil erosion in a watershed. During alfalfa growing season, there were 101 rainfall events in 2019 and 93 rainfall events in 2020, and only eight of these rainstorms

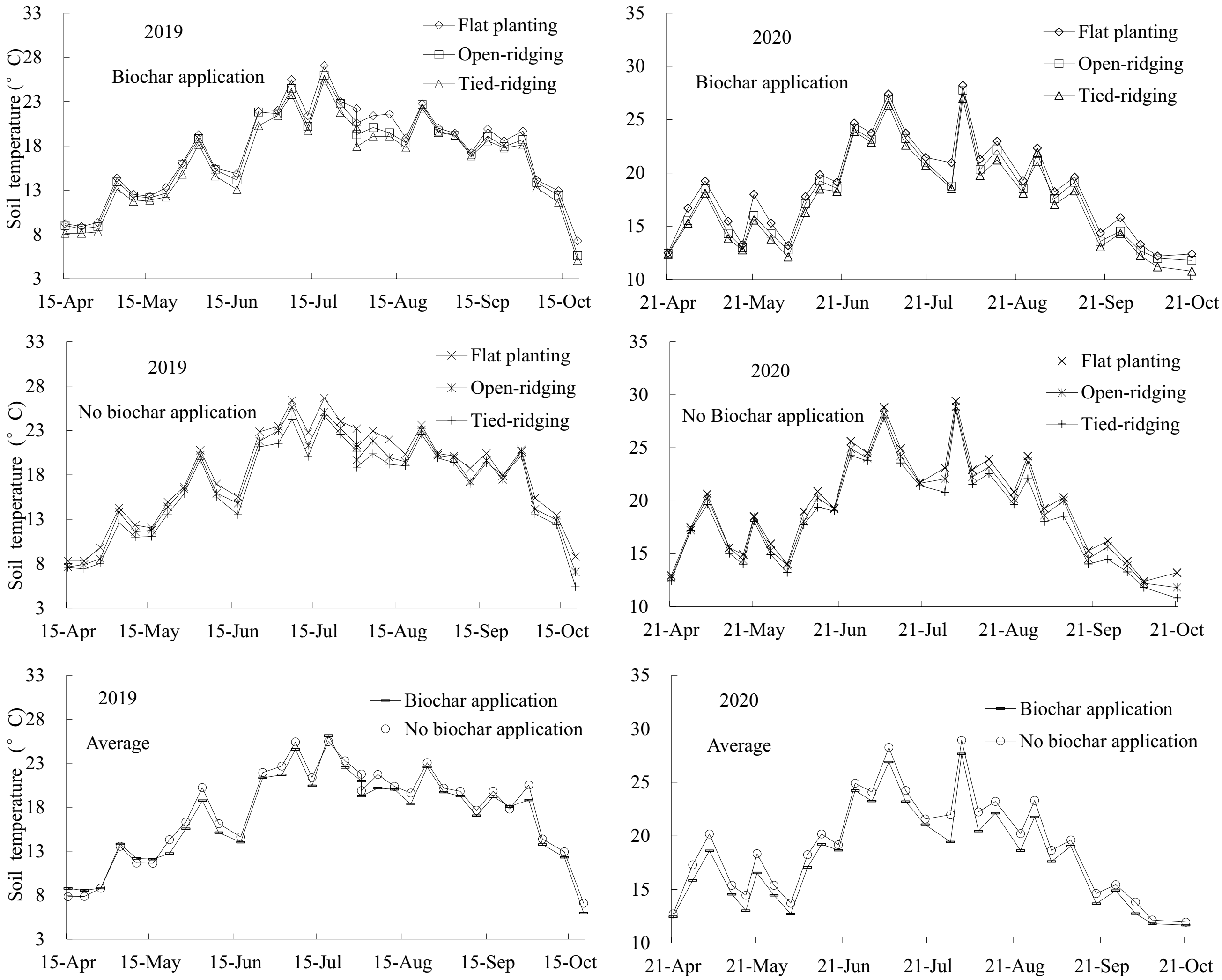

Fig. 5 Dynamics of topsoil temperature at furrow bottoms in 0–25 cm soil depth in ridge-furrow rainwater-harvesting with biochar application in 2019 and 2020

produced runoff and five rainstorms produced sediment in both years (Fig. 7). Compared to flat-planting, tied-ridging and open-ridging significantly reduced runoff, runoff coefficient, and sediment yield. Compared to no biochar application, biochar application significantly reduced runoff, runoff coefficient, and sediment yield. Compared to flat-planting, in 2019, the mean decrease of runoff for open-ridging and tied-ridging was 26.1% and 55.6%, respectively, under biochar application, while it was 35.0% and 40.8% under no biochar application; in 2020, the mean decrease of runoff for open-ridging and tied-ridging was 37.7% and 55.0%, respectively, under biochar application, while it was 20.0% and 33.5% under no biochar application. In 2019, the mean runoff coefficient for flat-planting, open-ridging, and tied-ridging was 7.92%, 6.11%, and 4.23%, respectively, under biochar application, while it was 11.59%, 8.35%, and 7.29% under no biochar application; in 2020, the mean runoff coefficient for flat-planting, open-ridging, and tied-ridging was 7.30%, 4.72%, and 3.47%, respectively, under biochar application, while it was 10.64%, 8.66%, and 6.91% under no biochar application. In 2019, the mean decrease of sediment yield for open-ridging and tied-ridging was 54.0% and 77.1%, respectively, under biochar application, while it was 55.0% and 62.1% under no biochar application. In 2020, the mean decrease of sediment yield for open-ridging and tied-ridging was 75.5% and 87.6%, respectively, under biochar application, while it was 65.2% and 81.6% under no biochar application. The mean runoff, runoff coefficient, and sediment yield for no biochar application were 1.48, 1.50, and 1.94 times greater than that for biochar application, respectively, in 2019, while it was 1.69, 1.70, and 2.25 times greater than that for biochar application in 2020.

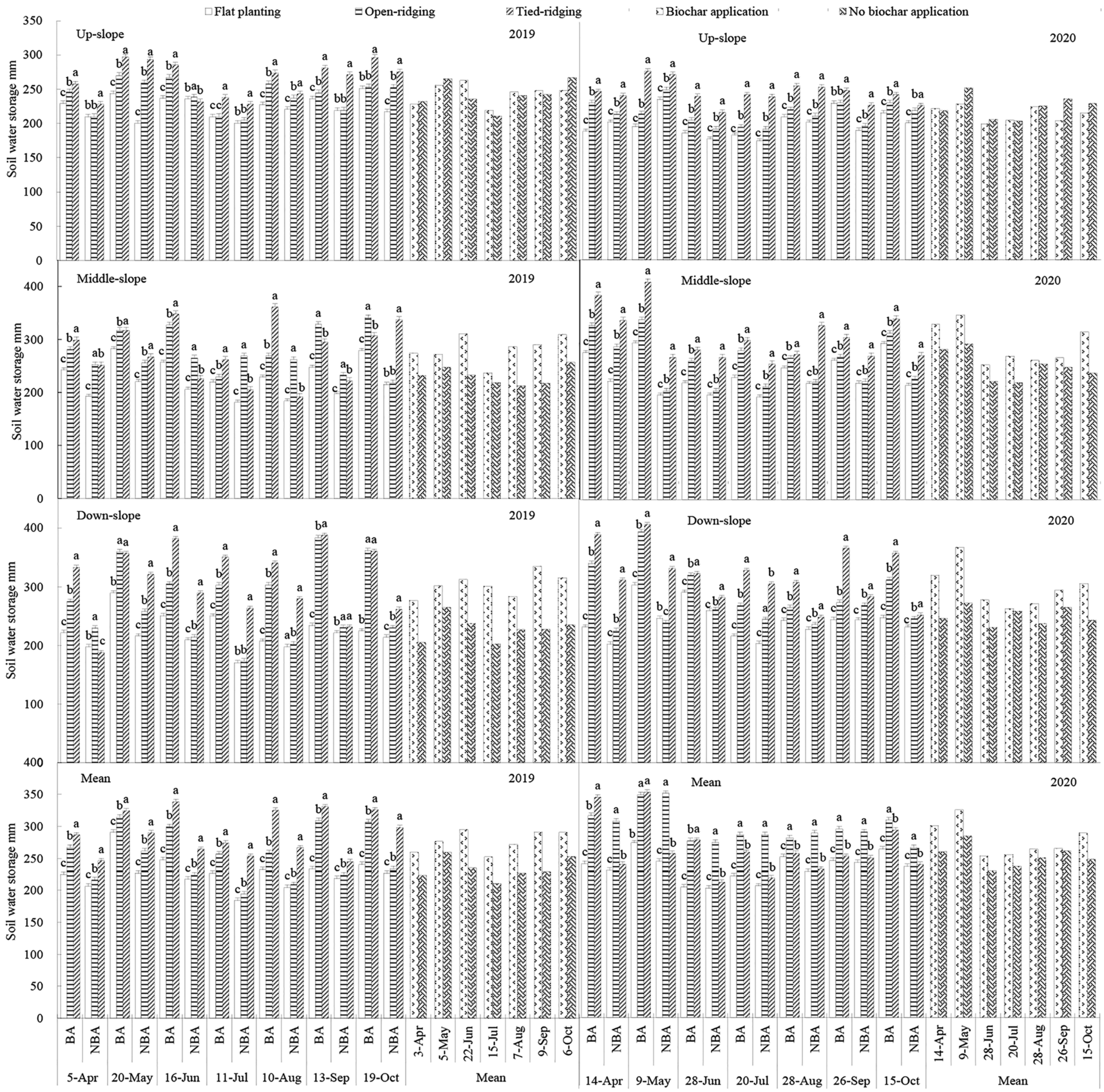

Fig. 6 Soil water storage at furrow bottoms in 0–200 cm soil depth in ridge-furrow rainwater-harvesting with biochar application in 2019 and 2020. BA, biochar application pattern; NBA, no biochar application pattern. The means (columns) labeled with the same letters within each group are not significantly different at the 5% level (Tukey's *b* test ANOVA)

3.4 Fodder yield and water use efficiency

Net fodder yield reflected single plant productivity and AFY reflected land productivity (Table 4). Net fodder yield was always greater than AFY. The following results and discussions on forage yield referred to AFY. In 2019, under biochar application and no biochar application, AFY for tied-ridging and open-ridging was significantly higher than that for flat-planting. There was no significant difference between tied-ridging and open-ridging. In 2020, under biochar application, AFY for tied-ridging was significantly higher than that for open-ridging, which was significantly higher than that for flat-planting. Under no biochar application, AFY for open-ridging was significantly higher than that for tied-ridging, which was significantly higher than that for flat-planting. Compared to flat-planting, in 2019, the increase of AFY for open-ridging and tied-ridging was 22.3% and 26.1%, respectively, under

Table 3 Analysis of variance combined over years for annual total runoff (ATR), annual total sediment (ATS), annual total actual fodder yield (ATAFY), and water use efficiency (WUE)

Source	Item	Tillage(T)	Biochar(B)	Year(Y)	T×B	T×Y	B×Y	T×B×Y	Error
ATR	df	2	1	1	1	2	2	2	24
	F	204.1	710.9	228.7	3.6	54.7	0.0	1.4	
	Sig	0.000	0.000	0.000	0.000	0.042	0.871	0.000	
ATS	df	2	1	1	1	2	2	2	24
	F	141.2	1711.5	509.6	100.8	1109.4	90.0	93.8	
	Sig	0.000	0.000	0.014	0.000	0.031	0.040	0.450	
ATAFY	df	2	1	1	1	2	2	2	24
	F	59.7	2.3	809.1	0.2	21.6	0.6	0.4	
	Sig	0.028	0.000	0.025	0.790	0.000	0.464	0.697	
WUE	df	2	1	1	1	2	2	2	24
	F	356.7	977.3	104.3	0.9	47.3	9.3	5.2	
	Sig	0.018	0.000	0.041	0.000	0.534	0.000	0.253	

biochar application, while it was 13.8% and 18.8% under no biochar application. In 2020, the increase of AFY for open-ridging and tied-ridging was 41.1% and 44.4%, respectively, under biochar application, while it was 38.6% and 34.1% under no biochar application. The mean AFY for biochar application was 1.06 times greater in 2019 and 1.11 times greater in 2020 than that for no biochar application.

Water use efficiency is an important indicator to measure the relationship between fodder yield and water consumption and reflects the water conversion efficiency in the process of plant growing. In 2019, under biochar application, WUE for open-ridging was significantly higher than that for tied-ridging, which was significantly higher than that for flat-planting. Under no biochar application, WUE for tied-ridging was significantly higher than that for open-ridging,

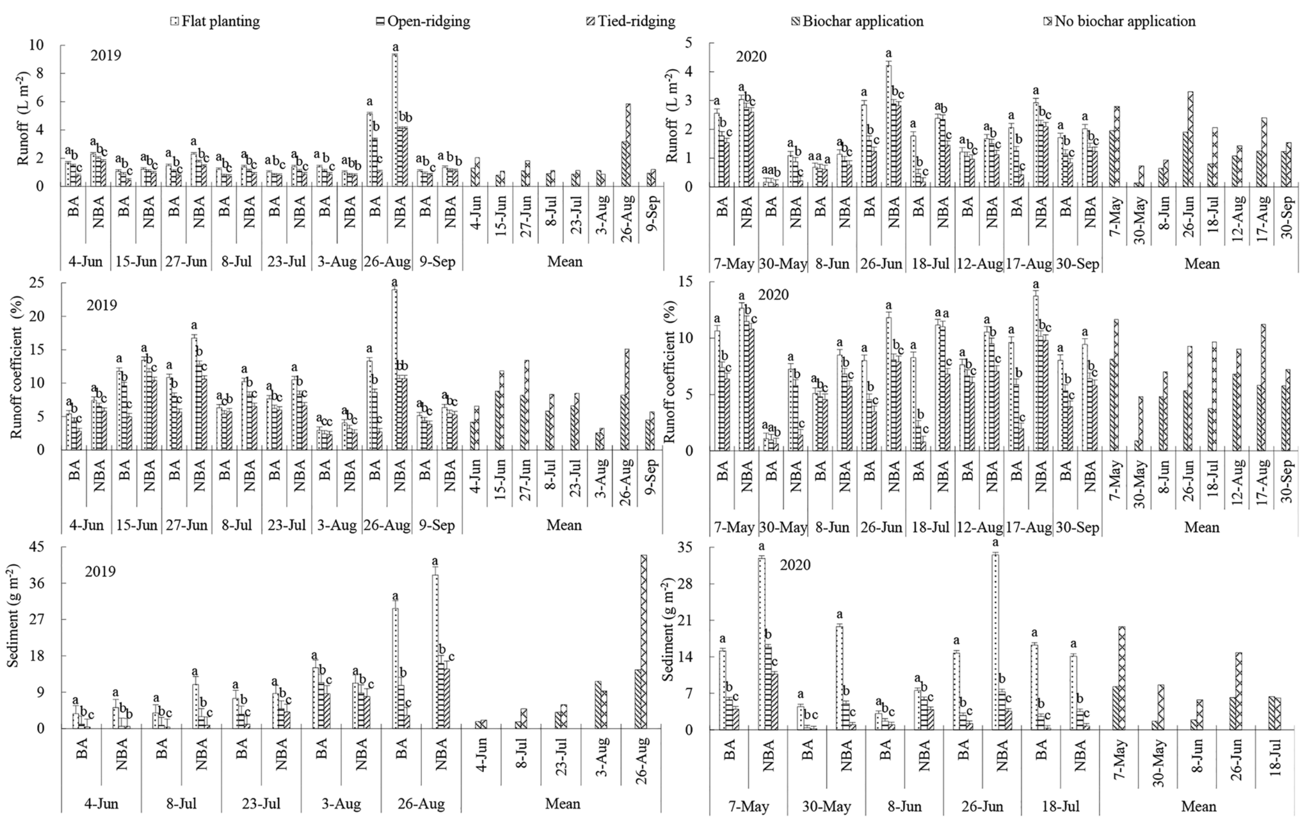

Fig. 7 Runoff, sediment, and runoff coefficient in ridge-furrow rainwater-harvesting with biochar application in 2019 and 2020. BA, biochar application pattern; NBA, no biochar application pattern. The means (columns) labeled with the same letters within each group are not significantly different at the 5% level (Tukey's *b* test ANOVA)

Table 4 Alfalfa fodder yield and water use efficiency (WUE) in ridge-furrow rainwater-harvesting with biochar application in 2019 and 2020

Biochar application	Tillage	Fodder yield (kg ha^{-1}) First cut NFY	First cut AFY	Second cut NFY	Second cut AFY	Third cut NFY	Third cut AFY	Annual total NFY	Annual total AFY	Increase (%)	WUE (kg ha^{-1} m^{-1})
2019											
BA	FP	1167c	1167c	318c	318c	/	/	1485b	1485b	0	10.93c
	OR	2927b	1378b	985a	438a	/	/	3912a	1816a	22.3	27.38a
	TR	3058a	1453a	867b	419b	/	/	3925a	1872a	26.1	28.39b
NBA	FP	1187c	1187c	282c	282c	/	/	1469b	1469b	0	7.29c
	OR	2787b	1270b	878a	403a	/	/	3665a	1673a	13.8	18.38b
	TR	2967a	1362a	756b	385b	/	/	3723a	1747a	18.8	20.28a
Mean	BA	2384	1333	723	392	/	/	3107	1724	5.5	22.20
	NBA	2314	1273	639	357	/	/	2952	1630	0	15.30
2020											
BA	FP	1728c	1728c	1027c	1027c	487c	487c	3242c	3242c	0	15.23c
	OR	5726b	2679b	2527b	1298a	1198a	597a	9451b	4574b	41.1	28.49b
	TR	5928a	2826a	2648a	1283a	1036b	572b	9612a	4681a	44.4	30.87a
NBA	FP	1628c	1628c	972c	972c	418c	418c	3018c	3018c	0	13.45c
	OR	5289b	2372a	2486a	1185a	1013a	627a	8788b	4184a	38.6	22.49b
	TR	5387a	2267b	2481a	1190a	987b	589b	8855a	4046b	34.1	24.73a
Mean	BA	4461	2411	2067	1203	907	552	7435	4166	10.0	24.86
	NBA	4101	2089	1980	1116	806	545	6887	3749	0	22.89

BA biochar application pattern, *NBA* no biochar application, *NFY* net fodder yield, forage yield based on furrow areas (exclude ridge and tied-ridge areas); *AFY* actual fodder yield, forage yield based on land areas of ridges (include ridge and tied ridge) and furrows; *FP* flat-planting, *OR* open-ridging, *TR* tied-ridging. Mean within a column followed by the same letters are not significantly different at the 5% level (Tukey's *b* test ANOVA) which was significantly higher than that for flat-planting. In 2020, under biochar application and no biochar application, WUE for tied-ridging was significantly higher than that for open-ridging, which was significantly higher than that for flat-planting. Compared to flat-planting, in 2019, WUE for open-ridging and tied-ridging increased by 16.45 and 17.46 kg ha^{-1} mm^{-1}, respectively, under biochar application, while it increased by 11.09 and 12.99 kg ha^{-1} mm^{-1}, under no biochar application. In 2020, WUE for open-ridging and tied-ridging increased by 13.26 and 15.64 kg ha^{-1} mm^{-1}, respectively, under biochar application, while it increased by 9.04 and 11.28 kg ha^{-1} mm^{-1}, under no biochar application.

4 Discussion

4.1 Soil temperature

The Loess Plateau of China was identified as one of the most impoverished and inhospitable areas to human life in the world due to its dry climate, barren soil, and harsh environment as reported by the United Nations World Food Program (Li et al. 2020b). Water deficiency is the main obstacle that limits agricultural production and precipitation is the sole water resource for agriculture production in these regions (Zhang et al. 2021). Tillage practice with biochar application in TRFRH provided potential possibilities to alleviate severe drought and soil erosion in this area (Habtemariam et al. 2019). Exogenous biochar, as an input additive, yielded corresponding outputs in RFRH with biochar application. This study demonstrated that RFRH with biochar application increased soil moisture and alfalfa fodder yield, and reduced sediment, runoff, and topsoil temperature.

Soil thermal properties play a vital role in seed germination, seed emergence, and yield formation (Usowicz et al. 2013). Soil temperature is influenced daily and seasonally by external environment (air temperature, solar radiation, and energy exchange between atmosphere and soil) and soil hydrothermal variation characteristics (soil texture, organic matter content, and particle size) (Xiong et al. 2020; Feng et al. 2021). The soil amended with biochar in planting furrows hindered the exchange of water, gas, and temperature between the soil and atmosphere (Acosta-Rangel et al. 2021). Moreover, the soil amended with biochar was considered as a buffer media between atmosphere and soil surface and hindered heat loss and water loss from the soil surface (Kan et al. 2021). The topsoil temperature variation in the soil amended with biochar was attributed to the integrated variations in soil albedo, diffusion, reflectance, and thermal conductivity (Usowicz et al. 2013). Black biochar-soil mixture is a kind of heat absorber, and easily absorbs the visible spectrum of solar radiation in the daytime. However, in the nighttime, biochar-soil mixture with a larger specific surface area and porosity could balance or even offset the heat absorbed from daytime (Usowicz et al. 2016). Biochar-soil mixture with a larger specific area and high porosity leads to a larger specific heat capacity of water and amount of thermal energy required for evaporation (Peng et al. 2011; Ge et al. 2020b). In the present study, before a high plant canopy establishment (May 2019), topsoil temperature at furrow bottoms for biochar application was noticeably greater than that for no biochar application. After a high plant canopy establishment, topsoil temperature at furrow bottoms for biochar application was noticeably lower than that for no biochar application. The topsoil temperature at furrow bottoms for biochar application decreased by 0.54 ℃ compared to no biochar application during alfalfa growing season over two years. Xiong et al. (2020) found that the topsoil temperature for biochar application (2% w/w) decreased by 0.93 ℃ compared to no biochar application. The existence of ridges and alfalfa canopy blocks solar radiation and decreases soil temperature. Compared to flat-planting, the mean topsoil temperature at furrow bottoms for open-ridging and tied-ridging decreased by 0.70 ℃ and 1.24 ℃, respectively, under biochar application, while it decreased by 0.69 ℃ and 1.33 ℃ under no biochar application over two years.

4.2 Soil water storage

Soil water storage was affected by precipitation, evapotranspiration, water infiltration, runoff, and soil physical properties (Zhang et al. 2019a; Qiu et al. 2021). Biochar has a large specific surface area and aggregates soil particles into soil-biochar aggregates (Li et al. 2020a). Soil-biochar aggregates increase soil water retention, water holding capacity and infiltration rate, and delay runoff generation time (Narjary et al. 2012; Palangi et al. 2021). In the present study, compared to no biochar application, the mean soil water storage at furrow bottoms for biochar application increased by 34.51 mm during alfalfa growing season over two years. Fu et al. (2019) indicated that the soil water content for full of biochar application and half of biochar application increased by 12.20% and 4.01%, respectively, compared to no biochar application. In TRFRH, tied-ridges, rainwater-harvesting-ridges, and furrows consist of a series of micro-catchment basins, which slows down runoff velocity and blocks runoff flow path by prolonging path flow tortuosity and furrow roughness (Lim et al. 2016; Habtemariam et al. 2019). This series of micro-catchment basins increased water infiltration time and retained surface runoff within furrows under high-intensity rainfall (Araya and Stroosnijder 2010). In the present study, compared to flat-planting, during the alfalfa growing season, the mean soil water storage at furrow bottoms for open-ridging and tied-ridging increased by 52.13 and 60.50 mm, respectively, under biochar application, while it increased by 39.50 and 31.24 mm under no biochar application over two years.

4.3 Runoff and sediment

Soil erosion caused by water is a significant cause of declining trends in land degradation and productivity (Haider et al. 2021). Cultivated land, especially sloping cultivated land, is the most erosion-prone land use type in this area (Liu et al. 2021). Water loss and soil erosion lead to soil nutrients loss, soil structure damage, soil aggregates dispersion, and soil bulk density improvement, and land productivity decline (Han et al. 2020; Yu et al. 2021). Runoff generation and sediment yield on sloping land is controlled by rainfall characteristics, vegetation cover, land use, soil antecedent moisture, slope gradient, and mulching material (Kumar and Dhorde 2021). In TRFRH, rainwater-harvesting-ridges, tied-ridges, and furrows reduce runoff velocity through increasing cross-section area, resulting in high sediment deposition time and low runoff transport capacity from furrows (Habtemariam et al. 2019). Biochar is a sustainable porous carbonaceous resource loaded with large pore spaces and strong sorption affinity, which increase infiltration rate and easily formed biochar-soil aggregates (Abrol et al. 2016). Biochar-soil aggregate absorbed and weaken rainfall potential energy, and delayed surface runoff generation (Lee et al. 2018). During alfalfa growing season over two years, compared to flat-planting, the mean decrease of runoff for open-ridging and tied-ridging was 31.9% and 55.2%, respectively, under biochar application, while it was 27.4% and 37.1% under no biochar application. The mean decrease of sediment yield for open-ridging and tied-ridging was 64.7% and 82.4%, respectively, under biochar application, while it was 60.1% and 71.8% under no biochar application. Mean runoff, runoff coefficient, and sediment yield for no biochar application were 1.60, 1.59, and 2.09 times greater than those for biochar application, respectively. Li et al. (2017) found that annual runoff and sediment yield for biochar application decreased by 19–28% and 11%, respectively, compared to no biochar application. The TRFRH with biochar application control runoff and prevent soil erosion.

4.4 Fodder yield and water use efficiency of alfalfa

Rainwater is collected from ridges and rainfall and runoff are coupled into furrows, leading to increase of soil water availability, fodder yield, and WUE of alfalfa in RFRH (Hu et al. 2020; Wang et al. 2021b). Hu et al. (2021) indicated that wheat yield increased by 66.3% for low biochar application rate (8×10^3 kg ha^{-1}) and 81.7% for high biochar application rate (16×10^3 kg ha^{-1}), compared to no biochar application. In the present study, the mean alfalfa fodder yield for biochar application was 1.10 times greater than that for no biochar application over two years. Compared to flat-planting, fodder yield for open-ridging and tied-ridging increased by 31.7% and 35.2%, respectively, under biochar application, while it increased by 26.2% and 26.5% under no biochar application, over two years. The high response of fodder yield and WUE to TRFRH was largely due to improved soil moisture conditions from increased use of low-intensity rainfall. In addition, RFRH with biochar application increased fodder yield and WUE of alfalfa by increasing soil moisture and reducing runoff and sediment yield.

Water use efficiency reflects the invisible relationship between soil water consumption and crop yield. Increases in WUE are commonly cited as plants in response to severe soil water deficit (Faloyea et al. 2019). The biochar-soil mixture on topsoil absorbed rainwater and prolonged water use time, and increased fodder yield and WUE of alfalfa (Han et al. 2016). Faloyea et al. (2019) showed that biochar-soil mixture significantly improved maize grain yield, biomass yield, and WUE, compared to no biochar application. Wang et al. (2018) reported that alfalfa fodder yield for open-ridging and tied-ridging increased by 32.7–34.6% and 20.2–20.6%, respectively, while WUE for those treatments increased by 4.78–4.89 and 4.06–4.57 kg ha^{-1} mm^{-1}, compared to flat-planting. In the present study, compared to no biochar application, WUE for biochar application increased by 26.9% over two years. Compared to flat-planting, WUE for open-ridging and tied-ridging increased by 14.86 and 16.55 kg ha^{-1} mm^{-1}, respectively, under biochar application, while it increased by 10.07 and 12.14 kg ha^{-1} mm^{-1} under no biochar application, over two years. Biochar is a kind of novel carbon-rich material and provides great potential positive effects on soil and water conservation and alfalfa fodder yield improvement in the Loess Plateau of China. The effects of biochar-amended soil on soil physicochemical characteristics, soil and water conservation, and crop yield strongly depend on biochar property, soil type, crop species, and farmland management practice.

5 Conclusions

A few heavy rainstorms caused runoff and sediment loss in ridge-furrow rainwater-harvesting with biochar application in this region. Ridge-furrow rainwater-harvesting with biochar application increased soil moisture, decreased runoff, sediment yield, and topsoil temperature, and increased soil moisture, fodder yield, and water use efficiency of alfalfa. Tied-ridging-furrow rainwater-harvesting with biochar application is a recommended planting technology for soil erosion control and fodder yield improvement in semiarid regions. Future research should investigate the mechanism of ridge-furrow rainwater-harvesting with biochar application on soil hydraulic conductivity, water retention, greenhouse gas emission.

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Declarations

Competing interests The authors declare no competing interests.

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