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Sediment control and fodder yield increase in alfalfa (*Medicago sativa* L) production with tied-ridge-furrow rainwater harvesting on sloping land

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ABSTRACT

Drought, water loss and soil erosion are the main factors restricting grain production and economic development in the semiarid hill areas of Loess Plateau, China. A field experiment was conducted to determine the effects of different tillage systems (open-ridging and tied-ridging) on soil water moisture, runoff, sediment yield, fodder yield and water use efficiency (WUE) on 2 slopes (5° and 10°), using traditional planting (without ridges and furrows) as a control, during 2 consecutive alfalfa growing years: 2015 and 2016. Results indicated that the benefits of fodder yield and WUE increase from tillage system were more effective than the benefits from slope gradient on slight sloping land. Open-ridging and tied-ridging decreased runoff and sediment transport and increased soil moisture, fodder yield and WUE of alfalfa. The decrease of sediment for open-ridging and tied-ridging was 85.1% and 88.4%, respectively, for slopes of 5°, while it was 83.9% and 89.0% for slopes of 10°. Only 7–10% rainfall events produced runoff and 4–6% rainfall events produced sediment. The mean runoff efficiency for traditional planting, open-ridging and tied-ridging was 11.6%, 9.1% and 6.7%, respectively, for slopes of 5°, while it was 13.4%, 10.0% and 7.8% for slopes of 10°, over 2 years. Increase of fodder yields for open-ridging and tied-ridging was 34.6% and 19.8%, respectively, for slopes of 5°, while it was 32.7% and 20.6% for slopes of 10°, over 2 years. The average WUE for open-ridging and tied-ridging was respectively 1.96 and 1.85 times greater than that for traditional planting, for slopes of 5°, while it was 1.88 and 1.77 times greater than that for traditional planting, for slopes of 10°, over 2 years. The mean runoff and sediment for slopes of 10° was 1.14–1.16 and 1.19–1.57 times that for slopes of 5°, respectively. The differences of fodder yield and WUE between slopes of 5° and slopes of 10° were not significant. Tied-ridging rainwater harvesting offered particular effects on water and soil conservation, while open-ridging offered particular effects on fodder yields and WUE enhancement during the first and the second growing seasons.

1. Introduction

Low precipitation, high evaporation, serious water loss and soil erosion are significant environmental hazards for crop production in semiarid regions of China (Kang et al., 2001; Chen et al., 2013). These regions are mostly characterized by hill and mountain topography with few large-scale plains for mechanical farming (Gong et al., 2006; Wei et al., 2015). The majority of the farm work is done by human and livestock labor as it is difficult for machinery to be used on small family farms. Loess soil is deep and the landscape contains many ravines. Most of the agricultural production is constrained by drought and poor soil fertility. The poor soil fertility is caused by water and wind erosion, especial in hillside areas (Chaplot and le Bissonnais, 2003). In addition to the scarcity and unpredictability of precipitation, about 10–30% of rainfall can be lost through surface runoff (Kang et al., 2001). Soil and water loss is a complex physical process involving cultivation, rainfall characteristic and soil properties. The traditional tillage system (mainly in monoculture and continuous cropping) cannot retain rainwater and

Abbreviations: RFRH, ridge–furrow rainwater harvesting; NFY, net fodder yield; AFY, actual fodder yield; ATAFY, annual total actual fodder yield; ET, evapotranspiration; WUE, water use efficiency; BD, bulk density; ATR, annual total runoff; ATS, annual total sediment

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control water loss and soil erosion during heavy rain events in hillside areas, resulting in poor rainfall utilization and ultimate soil degradation (Wei et al., 2015). Soil degradation is caused by soil nutrient loss and environmental deterioration (Chen et al., 2013). The only choice for subsistence farmers is to manage rainfall properly to minimize drought risk and control water loss and soil erosion. Ridge-furrow rainwater harvesting (RFRH) has been a successful tillage in reducing drought risk and controlling water loss and soil erosion in this area (Li et al., 2007; Gu et al., 2017).

The RFRH system usually consists of alternate parallel opening ridges and furrows on slightly sloping (< 20°) ground. Runoff and rainfall is coupled in furrows, resulting in deep water penetration and low water evaporation (Gan et al., 2013; Li et al., 2017a,b). The RFRH system has been adapted for several decades in agricultural and pastoral production in this area to minimize drought risk (Chen et al., 2013; Li et al., 2013; Zhao et al., 2014). One of the drawbacks of RFRH is cultivated area reduction as partial lands were built as ridges. Another of the drawbacks of RFRH is that furrows are ideal waterways. Ridge overtopping will occur and aggravate soil erosion when excess rainwater fully filled the furrows. This drawback can be overcome by connecting ridges with tied-ridges.

Tied-ridging is not a new technology, but it is one of the RFRH techniques that have been used in tree planting and grass cultivation in past decades in this region. Tied-ridging is known as boxed ridging, furrow diking, and furrow damming and basin tillage in other parts of the world (Jones and Stewart, 1990; Wiyo et al., 2000; Brhane et al., 2006; Nuti et al., 2009; Temesgen et al., 2009). In the tied-ridging system, rainwater harvesting ridges and tied-ridges form small basins, and rainwater harvesting ridges are blocked with tied-ridges. Tied-ridging has significantly decreased runoff, and increased water infiltration and consequently enhanced soil water storage and improved crop productivity in semiarid regions of Asia (Al-Seekh and Mohammad, 2008) and in semiarid tropics of Africa (Jensen et al., 2003; Motsi et al., 2004; McHugh et al., 2007). However, tied-ridging causes waterlogging, ridge overtopping and ridge failure during high intensity rainfall events, which has negative effects on soil water retention and crop yield increase (Jensen et al., 2003). The beneficial effects of tied-ridging on crop yield vary with amount and distribution of rainfall, soil type, slope, landscape position and crop (McFarland et al., 1991; Al-Seekh and Mohammad, 2009).

Slope gradient is one of the major topography factors affecting water loss and soil erosion (Chaplot and le Bissonnais, 2003; Assouline and Ben-Hur, 2006). It is necessary to understand that the effects of slope gradient on runoff, soil erosion and alfalfa growth for tied-ridging production in hilly areas. Jiang et al. (2014) indicated that runoff volume and sediment yield increased as slope gradient increased.

The Loess Plateau region is one of the largest alfalfa (*Medicago sativa* L) production areas in China (Gu et al., 2018). These regions are characterized by cool and dry air and large temperature differences between day and night during the summer. The deep-rooted characteristics and vigorous canopy of alfalfa help protect soil from being degraded. The amount of water loss and sediment transport from cropping fields is lower than that from ploughed bare fields (Kang et al., 2001). Wu et al (2011) found that alfalfa plots had higher resistance on soil erosion and sediment movement than did bare soil plots, because the overland flow containing sediment was retarded and blocked by the alfalfa plants.

The study of tied-ridging on soil moisture, runoff, soil erosion and alfalfa growth was limited in the Loess Plateau, especial on slopping land. Evaluation and understanding of runoff, sediment, and soil moisture status and crop yield are essential for the successful design and implementation of tied-ridging rainwater harvesting cultivation in this area, especial in hill area. The objectives of this research were to determine the benefit of tied-ridging on soil moisture, runoff, sediment, fodder yield, and water use efficiency (WUE) of alfalfa on different sloping lands in a semiarid region of China.

2. Materials and methods

2.1. The experimental site description

Field experiments were conducted at the Anjiagou Catchment during 2 consecutive alfalfa growing seasons: 2015 and 2016. The topography of the experimental station (latitude of 35°34′ N, longitude of 104°39′ E, has an altitude of 2075 m asl) is mountainous area with steep slopes. The experimental station is located 2–3 km east of Dingxi city, Gansu Province, Northwest China. The area is considered to be of semiarid medium temperate with a mean annual air temperature of 7.2 °C. According to records at Dingxi Meteorological Station, the mean annual precipitation was 384.8 mm (average values for 1971–2016), and the ratio of seasonal precipitation to average annual precipitation was 10.8%, 45.1%, 41.2% and 2.9%, respectively, for spring (from February to April), summer (from May to July), autumn (from August to October) and winter (from November to January). Monthly mean temperatures ranged from 1.1 °C in January to 19.1 °C in July. These sloping lands were converted from crop cultivation land into woodland or grassland after the 'Grain-for-Green Policy' was applied in 1990s. The soil in the study area was developed from wind-accumulated loess. According to the American soil classification system, this type of soil is defined as a calcic Cambisol (Chen et al., 2013). The soil bulk density ranges from 1.09 to 1.36 g cm^{-3} within a depth of 2 m, and the field water holding capacity is 20%–21%. The chemical properties of the soil are presented in Table 1. The farming practices were monoculture with crop harvesting only once in a year because of lack of heat and low temperatures. The major cultivated crops in the region are maize (*Zea mays*), potato (*Solanum tuberosum*), spring wheat (*Triticum aestivum*), flax (Linum usitatissimum) and proso millet (*Panicum miliaceum*). The major fodder grass species are alfalfa (*Medicago sativa*) and sainfoin (*Onobrychis viciifolia*).

2.2. Experimental design

Six field experimental treatments (2 slopes × 3 tillage systems) with 3 replications were carried out in a completely randomized arrangement. The three tillage systems were traditional planting (without ridges and furrows), open-ridging (without tied-ridges) and tied-ridging, respectively, while two slopes were of 5° and 10°. The rainwater harvesting ridge width was 45 cm and the height was about 15–20 cm, and the furrow width was 60 cm for the tied-ridging and open-ridging. According to local experience with replanting forest and grass, the up-ridge surface was arched with a slope angle of approximately 5–10°, while the down-ridge surface was arched with a slope angle of 50–60° approximately (Fig. 1). The height of the tied-ridges without mulching was 10–15 cm and its width was 20 cm (Fig. 2). The interval distance

Table 1
Chemical property of soil profiles in the experimental plots.

Depth (cm)	Total N (mg kg^{-1})	Total P (mg kg^{-1})	Total K (mg kg^{-1})	Organic matter (mg kg^{-1})	Ammonium N (mg kg^{-1})	Olsen P (mg kg^{-1})	Available K (mg kg^{-1})	pH
0–20	0.62	0.76	20.70	9.56	65.75	7.78	135	7.83
20–40	0.54	0.64	20.51	7.77	22.10	3.00	90	7.82