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The optimum ridge–furrow ratio and suitable ridge-covering material in rainwater harvesting for oats production in semiarid regions of China

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ABSTRACT

Drought, water loss and soil erosion are the main factors limiting agricultural production in semi-arid regions of China. A field study was conducted to determine (1) the runoff efficiencies of different ridge widths (30, 45 and 60 cm) covered with different materials (common plastic film, biodegradable mulching film and manual compacted soil) and (2) the effects of different ridge–furrow ratios (30:60, 45:60 and 60:60) and ridge-covering materials on soil water storage, topsoil temperature, hay yield, grain yield and water use efficiency (WUE) of oats in ridge–furrow rainwater harvesting (RFRH) system at the Dingxi Agri-meteorological station, during 2 consecutive years of 2012 and 2013. Average runoff efficiency was 18%, 20%, 22%, 71%, 77%, 83%, 76%, 77% and 84% for SR_{30}, SR_{45}, SR_{60}, BMR_{30}, BMR_{45}, BMR_{60}, CMR_{30}, CMR_{45} and CMR_{60} (SR, BMR and CMR were ridges with compacted soil, covered with biodegradable mulch film and common plastic film, respectively, and subscript numbers 30, 45 and 60 stand for ridge widths (cm)) over 2 years, respectively. The field experiment using oats as an indicator crop showed that mulching materials and ridge widths had distinct effects on topsoil temperature on the top of the ridges, but not in the bottom of the furrows. The soil water storage in the 140 cm depth of soil at the bottom of furrows increased with increasing ridge widths and in the order of $CMR \approx BMR > SR > FP$ (FP was the flat planting). The total precipitation was 414.4 mm in 2012 and 448.8 mm in 2013, which were higher than the average of rainfall (388.1 mm), leading to a significant increase of hay and grain yield in CMR, and an equivalent of hay and grain yield in BMR compared with FP in most cases. In the SR system, the positive effects of rainwater harvesting could not compensate for the negative effects of planting area reduction resulting in decrease in hay and grain yield. Compared with FP, the average grain yield decreased by 19%, 27% and 34% for SR_{30}, SR_{45} and SR_{60}, and increased by 6%, 4%, 1%, 12%, 9% and 6% for BMR_{30}, BMR_{45}, BMR_{60}, CMR_{30}, CMR_{45} and CMR_{60} over 2 years, respectively. The WUE of SR, BMR and CMR was 1.31, 1.41 and 1.47 times greater than that in FP over 2 years, and increased with increasing ridge width. The optimum furrow width was 32–38 cm for CMR and was 30–34 cm for BMR. Future study is needed to investigate the impact of RFRH on crop production, WUE and economic benefit under different precipitations, soil types, slopes and plant species using biodegradable mulching materials.

1. Introduction

The middle part of the loess plateau of Gansu province is one of China's most impoverished regions due to low precipitation and erratic climate. Food security has been made worse by drought, water loss and soil erosion conditions in this region. This region is strongly influenced by the monsoon climate, and

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Abbreviations: SR, ridge compacted with soil; BMR, ridge covered with biodegradable mulch film; CMR, ridge covered with common plastic film; FP, flat planting; WUE, water use efficiency; RFRH, ridge–furrow rainwater harvesting; HY, hay yield; GY, grain yield; ET, evapotranspiration; ANOVA, analysis of variance.

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approximately 60% of the annual precipitation occurs between June and September, during which times many crops, including oat (*Avena sativa* L) and wheat (*Triticum aestivum* L), have passed the key stage of requiring water (Qin et al., 2014). Most rainfall is in the form of low intensity (<5 mm) and cannot be utilized by crops, while a few thunderstorms usually causes tremendous water loss and soil erosion (Zhao et al., 2005). The drought in this region has shown an aggravated trend and the frequency of extreme rainfall events has also increased in the past 40 years (Qin et al., 2002; Zhao et al., 2005). Furthermore, surface water is limited and underground water stored deeply with high minerals content, and is unavailable for irrigation (Li and Gong, 2002a). On the other hand, the amount of evaporation in this region is very high (Li and Gong, 2002b). The agricultural production in this region mainly depends on the limited and erratic precipitation. The average long-term (1971–2013) annual precipitation in this region was 388 mm. As a result, droughts are common, and subsistence farmers are generally more concerned about availability of rainwater. Hence, the key to reduce surface runoff and increase agricultural productivity in this region lies in maximal utilization of precipitation by rainwater harvesting.

Ridge–furrow rainwater harvesting (RFRH) usually consists of alternate parallel ridges and furrows built along contours on sloppy lands, where the ridge is usually mulched with film for rainwater harvesting and the furrow is used for crop planting without mulching. This method is one of the most efficient technical applications for the maximizing utilization of rainfall, especial light rainfall, in semiarid regions (Deng et al., 2006). The RFRH collected runoff from ridges and rainwater coupled runoff in furrows leading to a deep soil water infiltration (Boers et al., 1986). This system was designed to promote infiltration and to store rainwater in the soil through the use of ridges, furrows and mulching film.

The major advantages of the RFRH system are that it is simple, cheap, replicable, efficient and adaptable (Reij et al., 1988). In addition to its economic benefit, the RFRH system has the potential to decrease evaporation with mulching, and to decrease runoff and to alleviate water loss and soil erosion using ridges built along contours (Gupta, 1995). The RFRH system can improve soil moisture storage, increase topsoil temperature, and enhance agricultural production in the areas with low temperature limitation (Li et al., 2000a,b). Qin et al. (2014) showed that potato tuber yields were increased by 36.3–86.8% with RFRH, while the water use efficiency (WUE) was increased by 33.5–83.9%, compared with conventional flat cultivation (without ridges and mulches) in this region. In addition to increasing crop yields, the RFRH system has become a valuable technique for reducing pressure of weeds and insect pests (Ramakrishna et al., 2006; Liu et al., 2009).

However, common plastic film mulching leads to a major environmental problem (white pollution) in soil, which is not good for plowing and plants growing. There is no treatment available to solve this problem at the moment. There are fewer results on application of biodegradable film in the RFRH system. Moreover, choosing the optimum ridge–furrow ratio and suitable ridge-covering material is of great importance for the development of the RFRH system in this region.

In recent decades, oats have been a main breakfast for human beings and an important fodder for farm animals, and have been widely cultivated in this region due to its longer growing seasons and higher drought tolerance than wheat. The object of this study was to determine effects of different ridge–furrow ratios and ridge-covering materials on production of oats, soil temperature, soil moisture storage and WUE in the RFRH system.

2. Materials and methods

2.1. Climate and soil characteristics

Field experiments were conducted at the Dingxi Arid Meteorology and Ecological Environment Experimental Station of the Institute of Arid Meteorology of China Meteorological Administration during 2 consecutive oats growing seasons in 2012 and 2013. The experimental station (latitude of 35°35′N, longitude of 104°37′E, and an altitude of 1896.7 m asl) lies in Dingxi city, Gansu Province, Northwestern China. The climate is of medium temperate and semiarid with mean annual air temperature of 7.2 °C, mean annual maximum and minimum air temperatures of 25.9 °C (July) and −13.0 °C (January). Mean annual precipitation was 388 mm (average values for 1971–2013), and around 56% of the precipitation occurs between July and September. The potential annual evaporation is about 1445 mm. Mean annual sunshine exceeds 2438 h, and the frost-free period is about 140 d ranging from 99 d to 183 d. The monthly mean air temperature and precipitation over the last 43 years showed a pattern of simultaneous heat and moisture. The soil at the experiment site is a loess-like loam with an average bulk density of 1.38 g cm^{-3} before sowing, and a field water holding capacity of 25.6%. The permanent wilting point of the upper 140 cm layer of the soil profile is 6.7% according to data from this agri-meteorological station. The physical and chemical properties of the soil are presented in Table 1. The farming practices were monoculture with crop harvesting only once in a year due to the lack of heat and the low temperatures. Major crops are spring wheat, maize (*Zea ways* L), oat, faba beans (*Vicia faba*), potato (*Solanum tuberosum*), millet (*Panicum miliaceum*) and oriental sesame (*Sesamum indicum*), and major forages are alfalfa (*Medicago sativa*) and Sainfoin (*Onobrychis viciaefolia*).

2.2. Experimental design

2.2.1. Runoff observation

The runoff plots, near the oats growing plots, were constructed for measuring the runoff efficiencies of different wide ridges covered with different materials (Fig. 1). Three mulching materials were common plastic film, biodegradable mulch film and compacted soil. The 3 ridge widths were 30, 45 and 60 cm. CMR, BMR and SR were abbreviated for ridges covered with common plastic film, biodegradable mulch film and compacted with soil. The common plastic film and biodegradable mulch film were mulched on ridges surface with the edges buried under in 3–5 cm depth soil along the bases of ridges. Compacted soil was made by hand during ridges banking, and became soil crust later after several rainfalls. The thicknesses of the common plastic film and the biodegradable mulching film were 0.008 mm. The common plastic film was manufactured by Shijiazhuang Yongsheng Plastic Plant Co Ltd, China, and biodegradable mulch film was manufactured by BASF Co Ltd, Germany. The biodegradable mulch film was composed of starch and other biomaterials. There were 9 treatments (3 ridge widths × 3 ridge-covering materials) with 3 replications in a complete randomized arrangement. The ridges (side-slopes of 40°) were 15–20 cm high. Each replication was a 10 m long ridge with a bucket. A cement block border, 8 cm high, was installed around the ridges to collect runoff water and to divert the water through 2 hoses into a bucket. Asphalt was sprayed on the surface of soil at the bases of the ridges to prevent runoff water permeating into the soil. Water-buckets, covered with lids with 2 small holes to prevent them from collecting precipitation and to prevent the evaporation of the collected runoff water, were placed at the ends of the 2 water hoses and installed in a 2 m deep field trench with its lids below the ground surface. A 250 l volume water bucket

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