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Assessing the effects of plastic film fully mulched ridge–furrow on rainwater distribution in soil using dye tracer and simulated rainfall

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ABSTRACT

The plastic film fully mulched ridge–furrow (FMRF) cropping system has been shown to effectively increase water use from rainfalls by crops in semiarid areas, though the proposed physical process and significance to harvest (or redistribute) rainwater in soil have never been experimentally reported. The present study was designed to visualize the path of rainwater infiltration and distribution in soils under three maize (*Zea mays* L.) cropping systems: flat plot (FP), ridge–furrow (RF), and FMRF. Narrow and wide ridges alternated in both RF and FMRF treatments while only in the FMRF treatment plastic film mulched the entire soil surface, with seepage holes through the film in the furrows. Dyed tap water was applied using a rainfall simulator. 24 h after applying simulated rain, soil surfaces and vertical soil profiles were photographed and staining features were used to indicate infiltration path and distribution of rainwater in the soil. The entire soil surface was dyed in the FP and RF plots whereas the dyed regions were confined only within narrow bands at the bottoms of furrows in the FMRF plots. In the vertical soil section perpendicular to crop lines, despite the similar area of dyed regions between three treatments, the maximum depth of the dyed regions across rainfall simulation durations increased by 47–72% and 129–156% in RF and FMRF, respectively, compared to FP treatment. In the vertical soil section (underneath the bottom of furrow for RF and RMRF) parallel to crop lines, the area of the stained regions increase d by 70–102% and 155–189% in RF and RMRF, respectively, compared to that in the FP treatment. In the vertical soil section either perpendicular or parallel to crop lines, the stained region matched the assumed maize intensely-rooted zone perfectly in the FMRF plots, but this matching was limited in FP or RF plots. In addition, the FMRF profoundly increased soil water content in the stained areas compared to FP or FR cropping system. Our study demonstrated that rainwater in soil has the greatest likelihood to be used by crops in FMRF among the three cropping systems.

1. Introduction

The Loess Plateau in China is an area of low crop productivity, mainly due to insufficient rainfall and low temperature. Recently, an in-situ water harvesting technique—the plastic film fully mulched ridge–furrow system (FMRF)—has proved to be a feasible way for improving rain-fed agriculture productivity (Gan et al., 2013; Liu et al., 2014). It has been suggested that applying this cropping system, precipitation on the plastic-mulched ridges converges into the furrows (where the crop is seeded) and then infiltrates into the rooted soil through perforations in the film (Gan et al., 2013; Liu et al., 2014). In addition, plastic mulch reduces soil water evaporation and increases soil temperature because the whole soil surface is covered. Benefiting from the alleviation of hydrothermal limitations under this cropping system, productivity is significantly improved in the temperature and rainfall limited areas in north China (Liu et al., 2009; Zhou et al., 2009).

In terms of its rainwater harvesting, the FMRF cropping could be an improved technique. Micro-catchment is a water harvesting technique (Abu-Awwad, 1999; Boers and Ben-Asher, 1982) and is used for agricultural, horticultural, and forest crops in semiarid areas (Carter and Miller, 1991). However, an ordinary micro-catchment (i.e., non-plastic-mulched ridge–furrows) may not be as effective as the FMRF system to collect rainwater from "ridges" to "furrows". The emergence of runoff on the ridges presupposes that the rainfall intensity exceeds the rate of water infiltration. Thus, the non-mulched ridge–furrow system may not be effective to collect rainwater from ridges to furrows during the light rain events if the rainfall duration is short. This is because rainwater can be absorbed in the soil matrix on the ridge shoulders, with little running into the furrows. In contrast, any amount of rainwater drizzled onto the plastic film above the ridges can flow

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Table 1
Selected soil physical properties (mean ± SE, $n = 3$) at the research site measured before plot establishment.

Soil depth (cm)	Bulk density (g cm^{-3})	Total porosity (%)	Saturated hydraulic conductivity (10^{-3} cm s^{-1})
0–10	1.16±0.04	56.74±4.22	4.41±1.60
10–20	1.18±0.02	52.18±0.23	3.10±0.59

along the slope due to the impermeability and hydrophobic nature of the film and then enter furrow soils through seepage holes in the film. On the Loess Plateau, light rains usually dominate over the events in spring and summer. In this regard, the plastic-mulched ridge–furrow system has been shown to effectively increase water use from light rainfalls by crops (Li et al., 2001).

However, the proposed physical process and significance of FMRF to harvest (or redistribute) rainwater has never been experimentally reported in literature. The dye-tracing method is used for providing direct information on path and distribution of water-flow in soil (Flury and Wai, 2003; Ghodrati and Jury, 1990). In the present study, the dyed water was sprinkled onto the soil surface of three different maize cropping systems—flat plot (FP), ridge–furrows (RF), and FMRF—to visualize the path of rainwater infiltration and distribution in the soil. The three treatments exactly mimicked three respective maize cropping systems on the Loess Plateau. It was more convenient to observe the process of rainwater entering the soil in the absence of a crop because the interference of the canopy is excluded. This scenario is relevant to the situation of maize germination and seedling stages (in the late spring and early summer) when the land surface is nearly bare and rainfall is scarce in semiarid regions of China. Our main objective was to assess the effect of the three maize cropping systems on the rainwater infiltration and distribution in soils.

2. Materials and method

2.1. Experimental design

The experiment was conducted on a flat conventionally-tilled field at Gansu Agricultural University Dingxi Experimental Station (35°28′N, 104°44′E; 1971 m a.s.l.), Gansu Province, China. The site has a mean annual air temperature of 6.4 °C, precipitation of 391 mm, and evaporation potential of 1531 mm. Most precipitation (68%) falls between June and September. The soil is developed from loess and classified as Ustorthents according to U.S. soil taxonomy (Soil Survey Staff, 1975). The soil contains 7.59 g organic carbon kg^{-1}, with a pH value of 8.4 in the top 10 cm. Soil texture is silty clay loam (2–0.05 mm, 7%; 0.05–0.002 mm, 63%; <0.002 mm, 30%) (Zhang et al., 2008). Before plot establishment, we measured soil bulk density, porosity, and saturated hydraulic conductivity in the top 20 cm layer (Table 1), following the methods described by Chen (2005). The bulk soil samples were taken using cutting rings (inner diameter 50.46 mm, height 50 mm).

The randomized complete block design had 9 treatment combinations (3 soil cropping patterns × 3 rain simulation durations), each replicated in 3 blocks (altogether 27 plots). The three maize cropping systems were FP, RF, and FMRF, respectively, and the three rain simulation durations were 2, 4, and 6 min, respectively, at a sprinkling intensity of 10 mm min^{-1}. On each of the RF and FMRF plots, narrow (15 cm high × 40 cm wide) and wide (10 cm high × 70 cm wide) ridges were alternated (Fig. 1). We assumed that maize plants were grown in all three treatments, with the same spacing (30 cm) in crop lines (or furrows) and the same density (about 57,000 plants ha^{-1}) in the fields, as those in the local farms. Because the narrow and wide ridges alternated in both RF and FMRF treatments, the spacing between furrows (where maize was seeded in a straight line) interchanged (Fig. 1). Therefore, we assumed that in the treatment of FP, the spacing between maize lines was also interchanged.

Two weeks before plot establishment, the field was tilled using a rotary cultivator to a 5 cm depth and was then carefully leveled. One week before rain simulation, three blocks were established on the field; the space between two adjacent blocks was 4 m wide, which severed an aisle. Each block was then divided into 9 plots, each measuring 10.89 m^{-2} (3.3 m × 3.3 m). On each of the RF and FMRF plots, narrow (15-cm high × 40-cm wide) and wide (10-cm high × 70-cm wide) ridges were prepared (Fig. 1). On each of FMRF plots, the whole land surface was tightly covered with polyethylene film (colorless and transparent, 0.008 mm thick and 1200 mm wide), and the perforations (around 1-cm in diameter; 30-cm apart, matching the plant spacing of 30-cm in a row) were drilled through the film in the furrows using a handheld device. These perforations helped rainwater collected from the ridges to enter the root zone in the FMRF cropping system. The transparent plastic film was used because the low temperature is a limitation for maize production in areas. All the 27 plots were finally covered by big plastic sheets with which the soil water evaporation was blocked during the time before rainfall simulation. This made sure that all soils in the different treatments had the same initial water content at the time of rainfall simulation.

2.2. Rainfall simulation and soil photographing

On the morning of April 10 2013, the big plastic sheets were removed from all 27 plots. Tap water was dyed with Brilliant Blue FCF at a concentration 3.0 g L^{-1} (Boll et al., 1992; Flury et al., 1994). The dyed water was then showered at 10 mm min^{-1} onto the

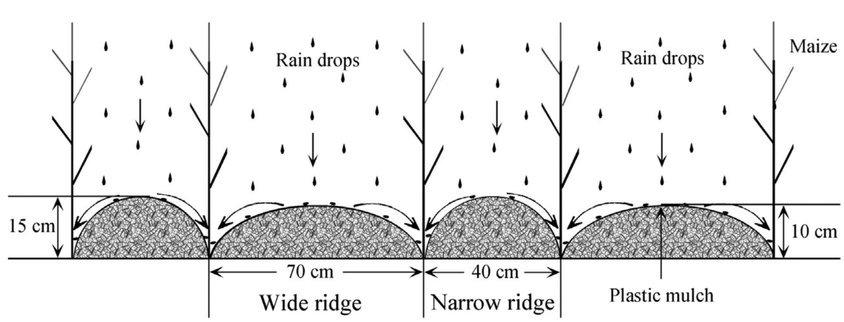

Fig. 1. Diagram showing plastic film fully mulched ridge–furrow maize cropping system, with maize seeded in furrows.