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Soil Wetting Patterns and Water Distribution as Affected by Irrigation for Uncropped Ridges and Furrows

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ABSTRACT

The ridge-furrow tillage combined with furrow irrigation is being more widely applied and has been shown to be effective in the Loess Plateau of China. Accurate characterization of water infiltration behavior under ridge-furrow irrigation could provide guidelines and criteria for future irrigation system design and operation. Our objective was to investigate soil water behavior during ponding infiltration in a cross-sectional ridge-furrow configuration. Soil water movement within three different soil textures was tested by tracking the spatial and temporal soil water content (SWC) variations in a soil chamber. The two-dimensional transient flow initially transferred rapidly, but gradually decreased with elapsed infiltration time, approaching a stable flow after 90 min. A technical parameter equation incorporating the Philip equation was developed using the water balance method to accurately predict total applied water volume (TAWV). The wetting patterns moved outward in an elliptical shape. The wetted lateral and downward distances fitted using equations accounted for capillary and gravitational driving forces in variably wetted soil media. Increasing initial SWC resulted in an increase in wetted soil volume, which can also be caused by decreasing bulk density in a homogeneous soil. Higher water level produced greater wetted lateral distance and more irrigation uniformity. The wetted lateral distance was almost identical to the wetted depth in silty clay loam soil; hence ridge-furrow irrigation should be implemented in such finer-textured soils. The wetted soil volume differed markedly among different soil textures (hydraulic properties), demonstrating that these properties can largely determine soil water spreading patterns and distribution.

Key Words: infiltration, ridge-furrow tillage, soil texture, soil water content, technical parameter equation, wetted soil volume

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INTRODUCTION

The ridge-furrow tillage method, which shapes the soil surface with alternate ridges and furrows along the contour, has been shown to improve soil water content (SWC) storage and agricultural water use efficiency in the Loess Plateau of China (Mbagwu, 1997; Li and Gong, 2002; Liu *et al.*, 2010). Incorporating furrow irrigation into ridge-furrow tillage fields is an increasingly popular method for applying water to crops that suffer from soil water deficit in this area (Li and Gong, 2002; Deng *et al.*, 2006; Liu *et al.*, 2010). The volume of lateral infiltrated water applied to ridges must meet the water requirements of the crops grown on the raised beds. The volume of wet soil and its wetted lateral distance in the soil profile are the limiting factors for determining the ridge-furrow width ratio and the spacing and number of planted rows. Excess irrigated water regularly causes deep percolation of water and nutrient (Chen *et al.*, 2011). Thus, increased lateral spreading and decreased moisture depth are desirable, so that the delivery of water throughout the root zone can minimize water leaching, nutrient loss, and groundwater pollution (Skaggs *et al.*, 2010). Because effective ridge-furrow irrigation design requires an understanding of the soil water movement during an infiltration event, characterization of the soil water distribution for two-dimensional soil profiles, especially the lateral moisture spreading process, is essential for uncropped ridge-furrow tillage systems.

Subsurface water flow is one of many critical and complex water flow processes that control surface runoff, infiltration, and water use efficiency (Tabuada *et al.*, 1995; Abbasi *et al.*, 2003). Variables affecting irrigated soil infiltration include physical properties of the soil and hydraulic parameters (Testezlaf *et al.*, 1987;

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Enciso-Medina *et al.*, 1998; Zhang *et al.*, 2005; Zhang *et al.*, 2012). Irrigation parameters such as the designed ridge-furrow geometry, water flow parameters, and applied water volume should also be considered (Abbasi *et al.*, 2003; Nie *et al.*, 2009; Chen *et al.*, 2011). These variables must be optimized in the design of efficient ridge-furrow irrigation systems. It is also important to achieve a stable infiltration state during a given infiltration event. The corresponding stable infiltration rate can be used to determine the optimal water application rate in an irrigation system (Mbagwu, 1997). Therefore, the variables incorporated in stable infiltration rate can be used to effectively estimate total applied water volume (TAWV).

The design of a ridge-furrow irrigation system requires an accurate estimation of the volume of wetted soil, the wetted lateral distance, and the soil water distribution. The wetted soil depth should be consistent with the anticipated depth of the root system, while its width should be correlated with the spacing of ridges and planting rows (Zur, 1996). A traditional method of describing water distribution is to determine SWC at selected nodes in the subsurface domain and draw ISO-water content lines (Bargar *et al.*, 1999; Abbasi *et al.*, 2003; Li *et al.*, 2003). Simulation experiments have been used to investigate the wetting distances under various irrigation conditions (Nie *et al.*, 2009; Chen *et al.*, 2011). Many numerical models have also been developed to simulate subsurface water flow during surface irrigation (Tabuada *et al.*, 1995; Ebrahimian *et al.*, 2011; Zhang *et al.*, 2013). Research on the effects of soil physical properties and irrigation parameters on the wetted volume is limited because of the difficulty of direct observation of wetting patterns in the soil depth. Furthermore, few studies that focused on two-dimensional soil water distribution could be applied to the efficient design of ridge-furrow irrigation systems.

In ridge-furrow irrigation, the depth dimension of water movement should coincide with the depth of the root system, while the lateral spreading distance can determine the optimum spacing and number of planting rows. Ponding infiltration in the cross-sectional ridge-furrow configuration was investigated in a soil chamber, which avoided the added complexity caused by plant uptake and site-specific factors. The objectives of this study were i) to analyze the physical infiltration process and develop the technical parameter equation using the water balance method and ii) to develop wetting patterns propagation equations to simulate the wetted lateral and downward distances in ridge-furrow irrigation systems.

MATERIALS AND METHODS

Laboratory experiment

The variables affecting the infiltration characteristics of uncropped ridge-furrow systems were tested with three soil types in a rectangular soil chamber. Heavy loam soil, medium loam soil, and light loam soil (Chinese classification system) were collected from 10 to 30 cm depth from fallow fields of the Loess Plateau, China. Some basic physical properties of the soils in the experimental fields are summarized in Table I. Particle size distribution and soil texture classification were determined according to Soil Taxonomy of the US Department of Agriculture. Soil textural fractions were analyzed using the Laser Mastersizer 2000 (Malvern Instruments, Malvern, England). Bulk density was determined by manually inserting a 50 mm by 50 mm ring soil sampler into a soil profile wall. Saturated SWC was measured on the soil samples using the oven-dried method. Saturated hydraulic conductivity was estimated using the ROSETTA code (Schaap *et al.*, 2001).

The experimental setup consisted of a rectangular soil chamber and water supply system (a Mariotte flask) (Fig. 1). The rectangular soil chamber, made from 10-mm-thick plexiglass material, was 70-cm long, 5-cm wide, and 70-cm high. The bottom of the soil chamber included many 2-mm parallel air vents for ventilation. The soil wetting pattern was inscribed on two selected vertical surfaces of the soil chamber to va-

TABLE I

Some physical properties of the soils tested in the experiment

Soil type	Particle size distribution			Texture classification	Bulk density	Saturated water content	Saturated hydraulic conductivity
	Sand (0.05–2.00 mm)	Silt (0.002–0.05 mm)	Clay (< 0.002 mm)				
	%				g cm^{-3}	cm^3 cm^{-3}	cm min^{-1}
Heavy loam soil	7.26±1.25[a]	64.83±2.24	27.91±2.66	Silty clay loam	1.36±0.01	0.49±0.01	0.009
Medium loam soil	16.17±3.49	66.39±1.49	17.44±2.01	Silt loam	1.45±0.04	0.50±0.01	0.018
Light loam soil	21.22±1.69	62.79±2.62	15.99±0.93	Silt loam	1.28±0.11	0.43±0.01	0.019

[a]Means±standard deviations ($n = 3$).