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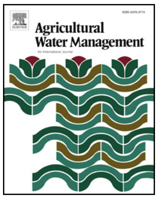

Simulation of soil water flow and heat transport in drip irrigated potato field with raised beds and full plastic-film mulch in a semiarid area

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ABSTRACT

Surface drip irrigation with full plastic-film mulch can increase crop yield and save water by regulating soil water and heat conditions for potato (*Solanum tuberosum* L.) production with raised beds in semiarid area where the rainfall is scarce and evaporation is high. For efficient use of plastic film mulch an understanding of the soil water flow and heat transport is needed. Here we use a model (HYRUS-2D) which is calibrated with field experiments to simulate soil water movement and heat transport. The field experiments were conducted with three treatments, characterized as wetted soil percentages: 35% (P1), 55% (P2), and 75% (P3). Furthermore, the effects of the uncertainty of key soil hydraulic parameters on soil water contents were evaluated using three approaches: (1) soil hydraulic parameters estimated from measured soil textural information (S1); (2) from experimentally measured soil water retention curve (S2); and (3) from inverse modeling (S3). The performance of S2 was the worst in all treatments; the root mean square error (RMSE) was > 0.05 $cm^3 cm^{-3}$. The performance of S3 was the best with RMSE ranged from 0.015 to 0.038 $cm^3 cm^{-3}$ at 10–50 cm soil depth. The simulated soil water in the raised bed decreased quickly after irrigation, maintaining adequate aeration for potato growth, irrespective of the wetted soil percentage. The downward transport of soil water still existed during the second and third days after irrigation in the simulations of the P2 and P3 treatments. The soil temperatures between the P1 and P3 treatments were similar. In conclusion, the HYDRUS-2D simulations could be used to estimate the soil hydraulic and thermal parameters with inverse modeling. The calibrated model can be used in the design and management of surface drip irrigation with raised beds and full plastic-film mulch to provide favorable soil water and heat conditions for potato growth.

1. Introduction

Surface drip irrigation with plastic-film mulching is widely used in agriculture and horticulture. The combination of surface drip irrigation and plastic-film mulching increases water and fertilizer use efficiency and crop yield (Assouline, 2002; Darwish et al., 2003; Tiwari et al., 2003; Phogat et al., 2014). Moreover, plastic-film mulch can modify the radiative and thermal conditions in the fields, which improves plant growth (Liakatas et al., 1986; Wang et al., 2011; Yaghi et al., 2013).

The advantages of this technology depend upon design and management which based on thorough understanding of spatiotemporal distribution of soil water and heat. The main goal is to match the soil wetted volume with root pattern and match soil water storage with crop evapotranspiration (Patel and Rajput, 2008). Many factors can affect the soil wetted volume, such as the soil hydraulic properties, emitter discharge, emitter spacing, wetted soil percentage, etc. The wetted soil percentage is an important parameter used in the design and management of drip irrigation system (Keller and Karmeli, 1974; Zur, 1996). Both soil water and heat stress can affect potato tuber growth, yield, and potato quality (Van Dam et al., 1996; Shock et al., 2007). It is, therefore, important to obtain soil water and heat dynamics in drip irrigated potato field under different wetted soil percentages with raised beds and plastic-film mulch.

Field experiments are costly, time-consuming, and site specific (Subbaiah, 2013). Therefore, analytical and numerical modeling methods are widely used to predict the soil water flow and heat transport and spatial-temporal distribution under various conditions (Coelho and Or, 1997; Cook et al., 2003; Šimůnek et al., 2008). Among these models, the HYDRUS model is popular and useful in simulation of soil water flow, solute, and heat transport (Šimůnek et al., 2008). This

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model has been used to simulate effects of different soil types and fertigation strategies (Gärdenäs et al., 2005; Hanson et al., 2006), emitter discharges (Ajdary et al., 2007), pulsed and continuous irrigation (Phogat et al., 2012, 2014), bed geometries (Holt et al., 2017), and partial plastic-film mulch (Liu et al., 2013; Chen et al., 2014; Wang et al., 2014; Li et al., 2015a,b; Holt et al., 2017; Qi et al., 2018) on soil water and solute transport under surface drip irrigation. The process of soil water and heat transport has also been simulated in winter wheat field with plastic-film mulch under no irrigation (Zhao et al., 2018). However, the effects of different wetted soil percentages on soil water flow and heat transport have not been evaluated with HYDRUS under surface drip irrigation with raised beds and full plastic-film mulch for potato crops. For potatoes in semiarid area, the raised beds and full plastic-film mulching can retain more soil water in plant root zone (Qi et al., 2018) and produce higher yield and water use efficiency in comparison to partial plastic-film mulch (Zhao et al., 2014).

Soil hydraulic parameters greatly affect the simulation results of soil water transport. Inverse models can be used to estimate soil hydraulic and thermal parameters (Šimůnek and Genuchten, 1996; Hopmans et al., 2002; Mortensen et al., 2006; Nakhaei and Šimůnek, 2014). In this study we validate the applicability of the inverse model with data from potato field. The objectives of this study are to: (1) evaluate the applicability of HDRUS-2D for soil water and heat simulation under drip irrigation with raised beds and full plastic-film mulch; (2) compare simulations of HYDRUS-2D results with soil hydraulic parameters derived from three different approaches (estimated from soil textural information, from experimentally soil water retention curve, and from inverse modeling); and (3) analyze the effects of different wetted soil percentages on soil water and heat transport and spatial-temporal distributions under surface drip irrigation with raised beds and full plastic-film mulch.

2. Materials and methods

2.1. Field experimental site and design

Field experiments were carried out at the Shiyanghe Experimental Station of China Agricultural University, located in Wuwei, Gansu Province (N 37°52′, E 102°50′, altitude 1581 m) from April to August in 2015. This region was characterized by a typical continental temperate climate with mean annual sunshine duration of 3000 h, mean annual temperature 8 °C, and mean annual accumulated temperature ($>$ 0 °C) 3550 °C which was suitable for potato growth. However, agricultural in this region was influenced by scarce water resources with mean annual precipitation of 164 mm, mean annual pan evaporation 2000 mm, and mean groundwater table 25–30 m below land surface.

Potato plants were drip irrigated in raised beds mulched by transparent plastic film and three wetted soil percentages were designed: 35% (P1), 55% (P2), and 75% (P3). Each treatment was replicated three times.

2.2. Agronomic and irrigation practices

The specific descriptions of agronomic and irrigation practices have been presented previously (Zhang et al., 2017a,b). In this manuscript, only main information was included to avoid overlapping. Seed potatoes (30 g, cv. Kexin No.1, Inner Mongolia Minfeng Potato Industry Co., Ltd., Ulanqab, China) were planted every 30 cm in the center of the raised beds at a depth of 15 cm on 15 April 2015. Each plot (6 m × 5.6 m) had 7 north-south raised beds (0.8 m wide and 0.2 m high) which were covered entirely using plastic film mulch (0.008 mm thick, 1.2 m wide). In 2015, 231 kg $\mathrm{ha^{-1}}$ P_2O_5 and 90 kg $\mathrm{ha^{-1}}$ N were spread before planting and 95 kg $\mathrm{ha^{-1}}$ N and 117 kg $\mathrm{ha^{-1}}$ K_2O were applied through irrigation after planting.

A drip tape (wall thickness 0.4 mm, inner diameter 16 mm) was placed on the soil surface in the center of each bed. The emitter discharge was 1.38 L $\mathrm{h^{-1}}$ at an operating pressure of 0.1 MPa. The drip irrigation system at each plot was managed by a sluice valve, a pressure gauge, a water meter, and a tensiometer. The irrigation application was started when the soil matric potential reached −25 kPa (Wang et al., 2007). The irrigation amount (in mm) was determined using the equation:

$$m = h(\theta_a - \theta_b)P/\eta \qquad (1)$$

where h is the planned wetted depth (cm) (equal to 50 cm for potato plants), θ_a is the volumetric soil water content after irrigation ($\mathrm{cm^3\ cm^{-3}}$) (equal to field capacity 0.27 $\mathrm{cm^3\ cm^{-3}}$ in this experiment), θ_b is the volumetric water content before irrigation ($\mathrm{cm^3\ cm^{-3}}$) (equal to 70% of field capacity), P is the percentage of wetted zone, and η is the coefficient of the efficiency of the drip irrigation system (equal to 0.97 for drip irrigation). The first irrigation amount was 19 mm for all treatments for potato emergence and the subsequent irrigation amount was 15 mm for the P1 treatment, 23 mm for the P2 treatment, and 31 mm for the P3 treatment. The actual irrigation amount used for the P1, P2, and P3 treatments was shown in Fig.1.

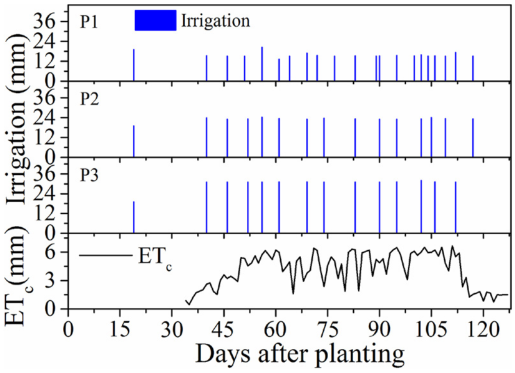

Fig. 1. The amount of each irrigation in 35% soil wetted treatment (P1), 55% soil wetted treatment (P2), and 75% soil wetted treatment (P3). The actual daily evapotranspiration (ET$_c$) during the growing season.

2.3. Weather, soil temperature, and soil water content measurements

Meteorological data (precipitation, solar radiation, relative humidity, wind speed, and air temperature) were measured with a standard automatic weather station (HOBO H21-001, Onset Computer Corp., Cape Cod, MA, USA) which was 2 m above the surface of the ground. Before the potato tubers were planted, sensors were installed to measure soil temperature and soil water content. The soil temperatures were measured on the soil surface, and at 5, 10, 20, 30, and 50 cm soil depths both in the middle and at the side (20 cm from the center) of the beds in one replication of each treatment. Soil water contents were measured with sensors at 10, 20, 30, and 50 cm soil depths in the middle, at the side, and at the base (40 cm from the center) of the beds in one replication of each treatment. Sensors on the soil surface and at 5 cm soil depth were thermocouples temperature sensors (ST10, Beijing Unism Technologies, Inc., Beijing, China). Sensors at 10, 20, 30, and 50 cm soil depths in the middle and the side of the beds were soil temperature/water sensors (FDS120, Beijing Unism Technologies, Inc.). Sensors at 10, 20, 30, and 50 cm soil depths in the base of the beds were soil water sensors (FDS100, Beijing Unism Technologies, Inc.). The placement of soil water sensors, temperature sensors, and soil temperature/water sensors was shown in Fig.2. The 10 min average soil temperature and soil water content were recorded automatically with a datalogger (SMC6108, Beijing Unism Technologies, Inc.).

2.4. Hydraulic parameter measurements

Before potato planting, soil samples were taken for soil particle size