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Simulation of water balance in a maize field under film-mulching drip irrigation

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ABSTRACT

Film-mulching drip irrigation technology has been widely promoted and used in arid regions. However, few studies have simulated the water balance process under film-mulching drip irrigation. In our study, the water movement in different soil layers and the distributions of evaporation and transpiration were evaluated using the HYDRUS-2D model. Long-term continuous observations of evapotranspiration, soil evaporation, crop transpiration and soil moisture in a maize field under film-mulching drip irrigation were conducted using an eddy covariance system, micro-lysimeters, stem-flow gauges and soil water sensors from 2014 to 2016 in northwest China. Experimental data were collected to calibrate and validate the model. Results showed that the accuracy of HYDRUS-2D was satisfactory in deep soil layers and that the RMSEs (root mean square errors) of the 20 cm, 40 cm, 60 cm and 80 cm soil layers were 0.022 $cm^3 cm^{-3}$, 0.018 $cm^3 cm^{-3}$, 0.014 $cm^3 cm^{-3}$ and 0.010 $cm^3 cm^{-3}$, respectively. Thus, the model could be improved to better simulate soil water in surface soil layers. The results suggest that HYDRUS-2D can generally be used to simulate the actual evaporation (Ea), transpiration (Ta) and evapotranspiration (ETa) in a maize field under film-mulching drip irrigation, with the REs (relative errors) of 1.7%, -11.06% and -8.27%, respectively. The simulation error of ETa mainly stemmed from the simulation error of Ta, and the error contribution was 91.02%. Therefore, further studies that consider the effects of film-mulching drip irrigation are needed to improve the root water uptake and the ET calculation modules and enhance the accuracy of the HYDRUS-2D model.

1. Introduction

Film-mulching drip irrigation is a new type of irrigation technology that combines drip irrigation with plastic film coverage (Hou et al., 2010). Unlike traditional drip irrigation, in film-mulching drip irrigation, a drip irrigation pipe system is first deployed at the soil surface, and a layer of plastic film is used to cover the drip irrigation pipe zone and soil surface. Hence, film-mulching drip irrigation technology combines the advantages of film-mulching technology, such as soil temperature enhancement and entropy conservation (Cook et al., 2006; Ghosh et al., 2006), and drip irrigation technology, such as water and fertilizer savings (Bowen and Frey, 2002; Romic et al., 2003) and yield increasing (Cheng and Zhang, 2000; Sun and Li, 2004). This technology has been widely used for various types of food crops, cash crops, fruit trees and flowers (Tiwari et al., 2003; Singh et al., 2007; Hou et al., 2010; Yaghi et al., 2013; Yang et al., 2016a; Yang et al., 2016b). In China, the film-mulching drip irrigation technology has been applied over approximately 4.7 million hm^2 in 29 cities and used in the cultivation of more than 40 crop types, including major field crops such as wheat, maize and cotton, which have exhibited yields that increased by more than 30% on average. Differing from traditional irrigation types such as border irrigation, furrow irrigation and drip irrigation, film-mulching drip irrigation is synergistically affected by both drip irrigation and film mulching, which influence the soil water infiltration patterns and boundary conditions. Determining how to accurately simulate the water balance process of a cropland system under film-mulching drip irrigation has become a popular research topic and attracted considerable attention in the field of hydrology.

Water balance theory is the basis for water cycles in the soil-plant-atmosphere continuum (SPAC). In recent years, many studies have been conducted to understand the SPAC mechanisms and have modelled the SPAC process (Chen et al., 2008; Manzoni et al., 2012; Jian et al., 2014; Chamizo et al., 2016). Due to the long period and high cost of field experiments, using models to predict the water balance in croplands is a cost-effective method because of the development of computers (Forkutsa et al., 2009; Šimůnek et al., 2011). Currently, the commonly

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used models include SWAP, SWAT and HYDRUS. Of these models, HYDRUS-2D can accurately simulate the water migration process in two-dimensional unsaturated soil with flexible boundary conditions and thus provides an important tool for simulating the cropland water balance (Tang, 2011). Modelling drip irrigation has become a popular application of HYDRUS-2D ever since Skaggs et al. (2004) successfully compared HYDRUS-2D simulations of drip irrigation with experimental observations (Šimůnek et al., 2016). And then, Li et al. (2004, 2005), Hanson et al. (2006, 2008, 2009), Roberts et al. (2008, 2009), Selim et al. (2012, 2013), Wang et al. (2014) did a lot of similar research on drip irrigation. However, few studies focused on drip irrigation under mulched conditions. For example, Liu et al. (2013) used HYDRUS-2D to simulate the temporal variations in the soil water content of a drip-irrigated cotton field under mulching. Li et al., (2015a),Li et al., (2015b) used HYDRUS (2D/3D) to evaluate the soil water distribution under a mulched drip irrigation system in an intercropping (tomato and corn) field. Evapotranspiration (ET) is one of the most important components of the hydrological cycle, and the results of ET estimations and analyses are crucial for effectively assessing the hydrology of a reconstructed landscape and for improving the associated design efficiency (Izadifar and Elshorbagy, 2013). The Penman-Monteith model (Mu et al., 2005), Shuttleworth–Wallace model (Li et al., 2013), VegSyst model (Gimenez et al., 2013), AquaCrop model and SIMDualKc model (Ran et al., 2017) have been used for evapotranspiration estimation; however, limited research has focused on HYDRUS-2D simulation results in this context. Ma et al. (2011) used HYDRUS-1D with a modified resistance equation to simulate the ET of winter wheat and summer corn under flooding irrigation, and the simulations were calibrated with eddy covariance data. Phogat et al. (2017) used HYDRUS-2D to estimate the water balance and ET components of subsurface drip-irrigated Chardonnay wine grapes, and the simulated values were then used to estimate the actual crop coefficients and water productivity.

Currently, HYDRUS-2D is mainly used for evaluations of various irrigation schemes, studies of root water uptake and groundwater recharge, and analyses of the transport of agricultural contaminants (Šimůnek et al., 2016). Although this model has been widely used for different crops, irrigation systems and mulches, maize, one of the most important crops, has been rarely studied using HYDRUS-2D under film-mulching drip irrigation, and the simulations of evaporation and transpiration are particularly rare. Further studies of film-mulching drip irrigation are needed, with a focus on scientifically establishing the boundary conditions of the relevant models and evaluating the accuracies of estimated soil water and ET values using the HYDRUS-2D model.

Therefore, in our study, long-term continuous observations of ET, soil evaporation, crop transpiration and soil moisture in a maize field under film-mulching drip irrigation were made using an eddy covariance system, micro-lysimeters, stem-flow gauges and CS616 soil water sensors from 2014 to 2016 in arid northwest China. With these observations, the accuracies of the soil water and ET simulations based on the HYDRUS-2D model were evaluated, and the error sources of the ET simulation were analysed to provide a reference and basis for improving and optimizing the model.

2. Materials and methods

2.1. Experimental site and description

The field experiments in 2014 and 2015 were conducted in a demonstration area of seeding maize under film-mulching drip irrigation; this area is part of a state-owned farm. The experiment in 2016 was conducted at Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of China Agricultural University. Both sites are located in Wuwei City, Gansu Province, Northwest China (N 37°52′, E 102°50′, elevation of 1581 m). The region is located in a typical continental temperate climate zone with 164 mm of annual precipitation and 2000 mm of mean annual pan evaporation. Moreover, the average annual duration of sunshine is 3000 h, the mean annual temperature is 8°C, and the annual cumulative temperature (> 0°C) is 3550°C. The groundwater table at the station is 40–50 m below the ground surface (Li et al., 2015a,b).

2.2. Experimental design

The width and interval of the plastic mulches were 1.2 m and 0.4 m respectively, and 4 seed rows and 2 drip lines were covered. Emitters were located every 0.3 m along the drip line, and the discharge rate was 3.2 L h^{-1}. The distance between neighboring drip lines under the same mulch was 0.6 m. The seeding maize was planted parallel to the drip lines with a row spacing of 0.25 m and planting spacing of 0.22 m. To provide evidence for improving the local field management, the irrigation amount and frequency during testing were consistent with the local standards.

2.3. Measurements in the maize field

As one of the most popular flux observation instruments, the eddy covariance (EC) system has the advantages of high measurement precision and fast sampling frequency. In 2014 and 2015, a new open-path EC system (model EC150) was installed in the maize field. Notably, the site had a very wide area of 2000 m × 1000 m that provided adequate fetch. The system consisted of a CO2/H2O open-path gas analyser (model EC150), three temperature and RH probes (model HMP 155 A), a Kipp & Zonen radiometer (model CNR4), two soil heat flux plates (model HFP01), a set of water content reflectometers (model CS616), a set of soil thermocouple probes (model TCAV), and an infrared radiometer (model S1-111). These instruments have been described by Qin et al. (2016). In 2016, the EC system was moved to a new experimental site with an area of 400 m × 200 m, as described in section 2.1. The probes were the same as those used in the EC system from 2014 to 2015. The EC150 and CNR4 sensors were installed 4.0 m above the ground level, and the HMP155 A sensors were set at heights of 2 m, 4 m and 6 m. Additionally, the HFP01 plates were set at a depth of 5 cm below the mulched soil and bare soil respectively. Five CS616 sensors were installed at 0.2 m, 0.4 m, 0.6 m, 0.8 m, 1.0 m, and the measured soil water content was calibrated based on the oven drying method.

The EC flux data were collected by a CR3000 data logger, and then converted into available data (30-minute interval) with Loggernet software. Due to the influences of weather and some other factors, Eddypro software was used to assess and correct the data before further analysis. The linear interpolation method was used for data gap filling when less than 4 observations were missed, and the MDV (mean diurnal variation) method was adopted when five or more observes were missing (Falge et al., 2001).

Stem-flow gauges (Flow32-1 K, Dynamax Co. USA) were used to collect maize transpiration measurements. The probes were installed on eight maize stems at the end of the jointing stage and data were collected with CR1000 data logger. The stem heat balance method (SHB) described in detail by Kigalu (2007) was used to measure the sap flow and transpiration rate in the plant stems. Three micro-lysimeters were buried under the mulch, and three others were set between mulch areas. All these micro-lysimeters were weighted at 7:00 am and 7:00 pm daily to determine the amount of soil water evaporation. The irrigation amount was controlled by water meters, and the leaf area was measured every week using a steel tape. The precipitation and wind speed at a height of 2 m were recorded by an automatic weather station (H21001, Onset Computer Crop., Cape Cod, MA, USA). The data were sampled every 5 s, and calculations were made every 15 min by a data logger (Table 1). The distributions of precipitation and irrigation were showed in Fig. 1.