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Evaluation of soil water dynamics and crop yield under furrow irrigation with a two-dimensional flow and crop growth coupled model

Jun Wang[a,b], Guanhua Huang[a,b,*], Hongbin Zhan[c], Binayak P. Mohanty[d], Jianhua Zheng[a,b], Quanzhong Huang[a,b], Xu Xu[a,b]

[a] Center for Agricultural Water Research, China Agricultural University, Beijing 100083, China
[b] Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing 100083, China
[c] Department of Geology and Geophysics, Texas A&M University, College Station, TX, USA
[d] Department of Biological and Agricultural Engineering, Texas A&M University, College Station, TX, USA

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ABSTRACT

Aiming at investigating an appropriate furrow irrigation management strategy for high melon yields and water productivity (WP), a new coupled model was developed based on the CHAIN_2D and the crop growth model of EPIC. In the coupled model, the root water uptake model of Vrugt was coupled with the root depth growth model in order to consider the interaction between root water uptake and crop growth. The coupled model was calibrated and validated with the observed values obtained from melon field experiment conducted in 2008 and 2009 in Gansu province, Northwest China. Simulation of total water use, leaf area index, melon yield and soil water dynamics fitted well with the field observations. The calibrated model was then used to predict the yield and water productivity (WP) of melon under different furrow irrigation scenarios. The relative yield and WP for different irrigation depth were considered as the criteria for investigating the appropriate irrigation management practices. Results showed that the relative yield and WP increased and decreased, respectively, as the relative irrigation increased through a quadratic function. The appropriate irrigation amounts for melon in the study area were 209 mm and 218 mm in 2008 and 2009, respectively.

1. Introduction

Water shortage is of great concern for crop production in the arid areas of northwest China (Kang et al., 2004). Melon is one of the main horticultural and cash crops in the oasis arid region of Shiyang River basin, Gansu Province, Northwest China. Furrow irrigation is one of the main irrigation methods for melon. Irrigation quota for melon is about 4050 m^3 ha^{-1}. Many studies indicated that the water use efficiency (WUE) in this area was very low (Kang et al., 1996) because of relatively high irrigation rates used by local farmers. Wöhling and Schmitz (2007) indicated that optimal water application control in irrigated agriculture had a high potential for increasing WUE and for creating sustainable irrigation system. However, field experiments are time-consuming and expensive. Therefore, process-based simulation tools with crop growth are required for evaluating and predicting crop yield and water requirement under furrow irrigation.

For furrow irrigation, a two-dimensional model should be used for soil water dynamics. Many models have been developed to simulate water flow in two-dimensional (2D) transport domain including SWMS_2D (Šimůnek et al., 2008), CHAIN_2D (Šimůnek et al., 2008), Nitrogen-2D (Lu et al., 2004). Among them, HYDRUS-2D (Šimůnek et al., 2008) is the most widely used model to simulate two dimensional movements of water, heat, and solute in variably saturated media. Recent studies have shown that HYDRUS-2D can be used to quantitatively evaluate deep percolation and nitrogen leaching under furrow irrigation with complex boundary conditions in the absence and presence of plants (Hanson et al., 2006; Doltra and Muñoz, 2010; Mmolawa and Or, 2003). Mailhol et al. (2007) applied HYDRUS-2D to evaluate the impact of water application condition on nitrogen leaching under furrow irrigation. Crevoisier et al. (2008) used HYDRUS-2D to simulate water and nitrogen transfer under two furrow irrigation technologies—every

* Corresponding author at: China Agricultural University, Center for Agricultural Water Research, Beijing 100083, China. Tel.: +86 10 62737144; fax: +86 10 62737138.
E-mail addresses: junwangcau@gmail.com (J. Wang), ghuang@cau.edu.cn (G. Huang), zhanhb@yahoo.com (H. Zhan), bmohanty@tamu.edu (B.P. Mohanty).

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furrow irrigation and alternative furrow irrigation. Ajdary et al. (2007) modeled nitrogen leaching from experimental onion field under drip fertilization by HYDRUS-2D. However, the interaction of crop growth and soil water dynamics was not considered in those above models. This may has significant effects on model accuracy, especially when applying it in arid irrigated areas. Thus, integration of the soil water model and crop model is crucial to describe the soil water dynamics and crop growth under furrow irrigation in this study area. The efforts on the integration had been reported in previous references. For example, Wöhling and Schmitz (2007) developed physically based coupled model for simulating 1D surface–2D subsurface flow and plant water uptake in irrigation furrow. In this model, crop growth was considered to simulate crop yield and actual evapotranspiration. However, a simple exponential function with uniform root density distribution was applied to describe the root water uptake, which cannot describe the root growth in the horizontal direction. de Willigen et al. (2002) indicated that root distribution pattern should be known *a priori* to estimate the 2D root water uptake potential. Vrugt et al. (2001) developed a 2D distribution function of root water uptake which allows spatial variations of water uptake under non-uniform and uniform water application patterns. This root water uptake distribution model has been successfully applied in HYDRUS model (Šimůnek et al., 2008) and APRI (Zhou et al., 2007). However, the above-mentioned 2D root distribution model does not consider root growth. Furthermore, Vrugt et al. (2001) indicated that the root water uptake distribution model can be adapted to account for root growth by allowing time-dependent Z_m and X_m values during a growing season. Therefore, it is necessary to develop a 2D framework with a simplified crop growth model and root water uptake distribution model considering root growth to simulate the soil water transport, root water uptake and crop yield in the vadose zone especially for an annual crop such as melon, which is the primary objective of this study.

Simplified models with easily measurable inputs were preferred at field production level (Wang and Smith, 2004). With less-demanding data input, the crop growth model of EPIC uses a unified approach to simulate the growth for more than 80 types of crops (Williams et al., 2006). Therefore, in this study, crop growth was simulated using a simplification of the EPIC crop growth model (Williams et al., 1989) including crop phonological development based on daily accumulated heat unit, a harvest index for partitioning grain yield, Monteith's approach (Monteith, 1977) for potential biomass, and water and temperature stress adjustments. Li et al. (2007) used the crop growth model of EPIC to develop the water and nitrogen management model (WNMM) for intensive cropping systems.

The objectives of this study are (a) to develop a model based on CHAIN_2D coupled with crop growth model of EPIC to simulate the dynamic root growth, root water uptake and crop yield under furrow irrigation, (b) to calibrate and validate the coupled model using melon field experimental data, and (c) to use the coupled model to estimate the yield and water productivity (WP) under different furrow irrigation scenarios for melon in the study area and subsequently obtain appropriate irrigation amounts for the study period.

2. Materials and methods

2.1. Field experiment

2.1.1. Experimental site

For the purpose of testing the proposed coupled model that will be described in detail later, we conducted experiments in the melon growing seasons of 2008 and 2009 at the Shiyanghe Experimental Station of China Agricultural University, located in Wuwei city, Gansu province, China (102°50′E, 37°52′N, altitude 1581 m). The experimental site is in a typical continental temperate climate zone, with a mean annual temperature of 8 °C, an average annual sunshine duration of 3000 h, a mean annual precipitation of 164 mm, a mean annual pan evaporation rate of about 2000 mm. The groundwater table is 40–50 m below the ground surface (Li et al., 2008).

Soils in the experimental site are sandy loam at the depth of 0–30 cm and silt loam at depths larger than 30 cm. The bulk density is in the range of 1.44–1.58 g cm^{-3}, field capacity ranges from 0.24 to 0.34 cm^3 cm^{-3}, and the wilting point ranges from 0.06 to 0.12 cm^3 cm^{-3}. The soil physical properties of the experimental site are presented in Table 1.

2.1.2. Experimental design

Huanghemi No. 3 (*Cucumis melo L.*), a widely growing melon species was used in the field trial. The sowing and harvesting dates were May 8th and August 25th, respectively. The emergence day of melon was May 17th. Irrigation water was applied to the field based on the lower soil water content (SWC) limit in the root zone. Each lower SWC limit corresponds to a percentage of field capacity (FC). The top 0–50 cm of soil layer was considered as the main root zone of melon in the following analysis according to Sensoy et al. (2007). Refilling to field capacity was performed as the average SWC in the root zone approached the proposed lower SWC limits for irrigation. There were two treatments, i.e. T1 and T2 which were applied in 2008 and 2009, respectively. The lower SWC limit for irrigation of T1 and T2 was 55% and 65% FC during blooming to swelling stages, respectively. The lower SWC limit during seedling and mature stages were 55% FC for T1 and T2. According to the results of the literature (Li et al., 2012), both treatments T1 and T2 can be considered as a moderately water stress treatment and a slightly water stress treatment, respectively. Each treatment had three replicates. The irrigation depth and timing of the T1 and T2 are shown in Table 2. Water was provided to the furrows by using a 20 mm diameter hose with an attached flow meter to record the applied water. The size of each subplot was 43.2 m^2 (8 m × 5.4 m), comprised of 6 rows with 17 plants per row. The spacing between rows and plants was 1.0 m and 0.5 m, respectively. The size of furrow and row is shown in Fig. 1. The furrow length is 8 m, and slop of the furrow is about 0.001. The furrow was partially covered by white plastic, a practice widely used in this area for many years. It covered 0.5 m of the soil and was placed on the row before melon seeding (Fig. 1). Besides, there was a 1-m empty gap between plots to eliminate any water disturbance from adjacent plots.

2.1.3. Measurement

Solar radiation, air temperature, rainfall, wind speed and relative humidity were measured every 15 min at a weather station (Hobo Weather Station, Campbell Scientific Inc., USA) which was about 50 m away from the experiment site.

The spatial distribution of melon root was measured using an 8 cm diameter auger. Soil cores were taken from three locations of furrow cross-section at depths of 20, 40, 60, 80, 100 cm on July 22th in the plots of T2 (Fig. 1) because few roots were found below the depth of 100 cm. The maximum root elongation in the horizontal direction is about 50 cm. In addition, soil core were taken from plant point to measure the root depth on DAE (day after emergence) 26, DAE42, DAE50, DAE67 and DAE98. The dimensions of each soil core sample were 8 cm (diameter) and 10 cm (depth). There were 28 samples to measure the root length density in the cross section of the furrow. Roots were washed from the soil core samples. The root length of each sample was measured by the scanner (Regent Instruments Inc., Canada), and the root length density (cm cm^{-3}) was calculated by the total root length over the soil core volume.