INTERNATIONAL JOURNAL OF AGRICULTURE & BIOLOGY
ISSN Print: 1560–8530; ISSN Online: 1814–9596
18–0976/2019/21–1–191–200
DOI: 10.17957/IJAB/15.0880
http://www.fspublishers.org

***Full Length Article***

# Modelling the Soil Water Dynamics under Micro-Sprinkling Hose Irrigation for Distorted Roots of Transplanted Cotton

**Hao Zhang[1], Hao Liu[2], Shunsheng Wang[1], Xuan Guo[1], Xuewen Gong[1] and Jingsheng Sun[2*]**
[1]*School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China*
[2]*Key Laboratory of Crop Water Use and Regulation, Ministry of Agriculture, Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences, Xinxiang 453002, China*
[*]For correspondence: jshsun623@163.com; abelzhanghao@outlook.com

## Abstract

Information on root zone water dynamics is essential to optimize irrigation strategies. The study on root is an important step for the research of root zone water dynamics. A field experiment was carried out to study the root development of transplanted cotton and simulate root zone water dynamics under micro-sprinkling hose irrigation (MHI) with different irrigation regimes during 2013–2015. The irrigation regimes were set as: high irrigation (HI, 80 mm), medium irrigation (MI, 60 mm) and low irrigation (LI, 40 mm). Analysed data disclosed that the root system of transplanted cotton consisted of some claw-shaped branch roots, and was distributed in shallower soil layer (0–30 cm) than that of direct-seeded cotton. The average root length density in the MI treatment was 12 and 41% larger than that in the HI and LI treatments. MI also increased the average root biomass density by 18 and 53% compared with HI and LI. By inputting the calibrated data on distorted root, HYDRUS-2D model simulated the soil water content well. The mean average absolute errors, root mean square errors, model efficiencies, and $R^2$s in the HI treatment were 0.009 m$^3$ m$^{-3}$, 0.015 m$^3$ m$^{-3}$, 0.825 and 0.839; these in the MI treatment were 0.011 m$^3$ m$^{-3}$, 0.017 m$^3$ m$^{-3}$, 0.859 and 0.863; and these in the LI treatment were 0.010 m$^3$ m$^{-3}$, 0.015 m$^3$ m$^{-3}$, 0.900 and 0.894, respectively. In summary the HYDRUS-2D can be used to simulate the root zone water dynamics in transplanted cotton field and irrigation regime of 60 mm proved better than 80 and 40 mm to promote the root growth of transplanted cotton under MHI. 

**Keywords:** Root system; Root length density; Soil water content; HYDRUS-2D; Irrigation regime

## Introduction

The Yellow River Basin in the North China plain (NCP) is not only a main cotton-growing region, but also an important crop-growing region of China (CRI, 2013; Dai and Dong, 2014). With economic development and rapid urbanization, cotton is competing with grain crops for cultivated land. The agricultural development in China, especially in the NCP, is restricted by the shortages of good-quality cultivated land and freshwater (Dong *et al.*, 2006; CRI, 2013; Luo *et al.*, 2015). Research shows that the transplanting technique combined with water-saving irrigation method can improve the utilization efficiency of cultivated land and guarantee the harvest of both grain crops and cotton (Dong *et al.*, 2007; CRI, 2013; Shah *et al.*, 2017). Compared with the traditional method of intercropping winter wheat and cotton, transplanting cotton after wheat harvest can improve agricultural mechanization level and increased winter wheat yield (Dong *et al.*, 2005; Zhang *et al.*, 2007, 2008). Meanwhile, the greatest spreading period of cotton *Fusarium* wilt and *Verticillium* wilt in the NCP (from May to June) is partially avoided by the transplanted cotton (Ma *et al.*, 2010). However, transplanted cotton belongs to a short-season cotton, and the whole growth period in the field is only about 128 d, which mainly concentrates in the hot summer in the NCP (from June to September) (Liu *et al.*, 2017). The summer weather in the NCP requires that soil water content (SWC) must be enough to ensure the water consumption by evapotranspiration. Whereas, moderate deficit irrigation can significantly improve water use efficiency, and is also beneficial to cotton growth (Sampathkumar *et al.*, 2013; Luo *et al.*, 2016; Rao *et al.*, 2016). Therefore, exploring and modelling soil water dynamics to guarantee appropriate SWC in the root zone is not only beneficial for improving water use efficiency, but also critical for the growth and yield of transplanted cotton.

The study on root is the first step for the simulation of the root zone water dynamics. During transplanting the cotton seedlings into field, many fine roots of cotton seedling were damaged, which was unfavorable for the root development of transplanted cotton in the field (Dong *et al.*, 2005, 2007). Mao *et al.* (2008) made a preliminary observation of transplanted cotton roots and found there were many differences for the root morphology between

**To cite this paper:** Zhang, H., H. Liu, S. Wang, X. Guo, X. Gong and J. Sun, 2019. Modelling the soil water dynamics under micro-sprinkling hose irrigation for distorted roots of transplanted cotton. *Intl. J. Agric. Biol*., 21: 191–200

transplanted and direct-seeded cotton. At present, there are many research efforts focused on the root of direct-seeded cotton (Min *et al.*, 2014; Ning *et al.*, 2015; Rao *et al.*, 2016). Hu *et al.* (2009) found that the cotton root weight was very high under 75% field water capacity. Hulugalle *et al.* (2015) evaluated cotton root growth using a combination of Minirhizotrons and soil core sampling, and he found that, compared with continuous cotton pattern, the cotton-wheat rotation pattern could promote the cotton root growth in the subsoil (60–90 cm). As few studies on the effect of irrigation regimes on the transplanted cotton root have been carried out, we conducted experiment to explore the differences of transplanted cotton root under micro-sprinkling hose irrigation (MHI) with different irrigation regimes. MHI has the advantages of both sprinkling and drip irrigation (*e.g.*, high irrigation water use efficiency, high irrigation uniformity and good anti-clogging performance) (Zhang *et al.*, 2009; Man *et al.*, 2014). Due to these advantages, MHI has been gradually adopted in the NCP in recent years (Man *et al.*, 2014).

The root data obtained from the experiment were used to determine the root parameters in HYDRUS-2D. HYDRUS-2D was employed as a tool for simulating soil water dynamics. It is a hydrologic model applied to the variably-saturated porous media incorporating water extraction by roots and evaporation from the soil surface. HYDRUS-2D is based on the Richards equation and has received a great deal of attention (Bufon *et al.*, 2012; Elmaloglou and Diamantopoulos, 2013; Han *et al.*, 2015; Mguidiche *et al.*, 2015). Previous simulation studies have shown that the simulated outputs of HYDRUS-2D were in reasonable matching with measured values (Kandelous *et al.*, 2011; Phogat *et al.*, 2012; Li *et al.*, 2017).

The root growth differences between direct-seeded and transplanted cotton and the effect of irrigation regimes on transplanted cotton root growth are not known well. The applicability of the HYDRUS-2D model for the simulation of root zone water dynamics in transplanted cotton field is also unknown. We hypothesized that the irrigation regime may have a significant effect on the root development of transplanted cotton, and the root zone water dynamics in transplanted cotton field can be accurately simulated by the HYDRUS-2D model. The study on root development and root zone water dynamics in transplanted cotton field will be helpful for the further understanding of transplanted root system and the design of irrigation regime in transplanted cotton field.

## Materials and Methods

### Experimental Site and Design

**Site description:** This study was conducted from 2013 to 2015 at the Experimental Station of Farmland Irrigation Research Institute, Chinese Academy of Agricultural Sciences (35°18′ N, 113°54′ E, altitude 73.2 m). The experimental site belongs to a warm temperate climate region. The frost-free days in the experimental site is 220 d, the mean annual potential evaporation is 2000 mm, the mean annual sunshine duration is 2286 h, the mean annual rainfall is 546 mm, and the mean annual temperature is 14.2°C. The average groundwater table is below 5 m. Some soil properties in the experimental site are listed in Table 1.

**Experiment 1:** In Experiment 1, the root characteristics of transplanted and direct-seeded cotton were compared. For the transplanted cotton, the cotton seeds (Zhongmiansuo 50) were sown in separate cotton plug-seedling on May 11, 2013, May 6, 2014 and May 6, 2015, respectively. Cotton seedlings were raised in substrate (turf:vermiculite:perlite = 5:4:1) in greenhouse. When the cotton seedlings grew in greenhouse for the periods of one month, they were mechanically transplanted into the fields with row spacing of 70 cm; the plant space in each row was 20 cm. According to the local recommended fertilizer practice, 450 kg ha$^{-1}$ of compound fertilizer (N:P:K: 18, 18 and 18% composite) was applied to the soil as a basal fertilizer. After the squaring stage, 150 kg ha$^{-1}$ of urea (N: 46%) was applied. The bolls were picked by hand two times each season. The first picking was conducted when approximately 50% of the bolls opened. The last picking was conducted when the remaining bolls opened. The last picking dates were October 20, 2013, October 13, 2014 and October 15, 2015, respectively. For the direct-seeded cotton, the cotton seeds (Zhongmiansuo 50) were sown on May 20, 2015. With hill-drop planting method by hand, four or five seeds per hill were hand dropped into the prepared furrow at in-row plant space of 20 cm. The seeds in furrows were covered with moist soil. When most seedlings reached the two-true leaf stage, only one vigorous plant per hill was left. Other management practices in direct-seeded cotton field were conducted according to those in transplanted cotton field.

**Experiment 2:** Experiment 2 explored the effect of different irrigation regimes on the root system of transplanted cotton under MHI. The experiment was conducted in a completely randomized design, and comprised of three irrigation regime treatments under MHI. The irrigation regimes were set as: high irrigation (HI, 80 mm), medium irrigation (MI, 60 mm) and low irrigation (LI, 40 mm). There were three repeated plots per treatment. The size of each plot was 15.0 m long and 10 m wide. The folded diameter of micro-sprinkling hose was 60 mm, and the length was 15 m. Under the condition of no wind and canopy cover, the sprinkling distance of MHI was 4 m. At the working pressure of 0.4 MPa, the irrigation flow of 1 m long hose was 0.165 m$^3$ h$^{-1}$ m$^{-1}$. After transplanting cotton seedlings, micro-sprinkling hoses were placed between two transplanted cotton rows, maintaining a spacing of 1.4 m. The irrigation scheduling and rainfall during the experimental seasons from 2013–2015 are shown in Table 2. After the cotton seedlings were transplanted, irrigation was first conducted to guarantee the survival of the cotton seedlings.

**Table 1**: Soil physical properties and calibrated parameters of the van Genuchten-Mualem model at the study area

| Soil layer (cm) | 0-20 | 20-40 | 40-60 | 60-80 | 80-100 |
|---|---|---|---|---|---|
| Soil texture | Loam | silt loam | silt loam | silt loam | sandy loam |
| Clay (%) | 4 | 7 | 6 | 5 | 2 |
| Silt (%) | 43 | 45 | 48 | 47 | 17 |
| Sand (%) | 53 | 48 | 46 | 48 | 81 |
| Bulk density (Mg m$^{-3}$) | 1.56 | 1.58 | 1.54 | 1.42 | 1.45 |
| Field capacity (m$^3$ m$^{-3}$) | 0.34 | 0.31 | 0.33 | 0.28 | 0.29 |
| è$_r$ (m$^3$ m$^{-3}$) | 0.127 | 0.096 | 0.095 | 0.107 | 0.066 |
| è$_s$ (m$^3$ m$^{-3}$) | 0.467 | 0.417 | 0.424 | 0.487 | 0.501 |
| $K_s$ (cm d$^{-1}$) | 27.6 | 9.7 | 4.7 | 12.6 | 84.7 |
| á | 0.012 | 0.017 | 0.022 | 0.009 | 0.012 |
| *N* | 1.54 | 1.31 | 1.21 | 1.46 | 1.88 |
| *L* | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |

Note: Soil texture was determined according to the international soil texture classification system. Saturated water content ($\theta_s$) and saturated hydraulic conductivity ($K_s$) were measured values, whereas $\theta_r$, α and *n* were estimated through inverse simulation

**Table 2:** Irrigation scheduling and rainfall during the experimental seasons from 2013-2015

| Year | Precipitation (mm) | Irrigation amount (mm) | | | Irrigation date |
|---|---|---|---|---|---|
| | | HI | MI | LI | |
| 2013 | 319.5 | 160 | 120 | 80 | June 13, August 21 |
| 2014 | 450.2 | 160 | 120 | 80 | June 6, July 17 |
| 2015 | 211.7 | 240 | 180 | 120 | June 10, July 12, August 20 |

Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

## Sample Collection and Analyses

**Distribution of root morphology:** A soil core method was employed to measure the root length density (RLD) and root biomass density (RBD) of transplanted cotton (Salgado and Cautín, 2008). The measurement was conducted only at the critical periods for the water consumption (4 August, 2013, 13 August, 2014 and 16 August, 2015). Sites without weeds in the field were selected and a 70 cm-deep, 35 cm-wide and 10 cm-thick soil sample was dug out. The soil samples were replicated thrice per treatment (one per treatment plot). We soaked the soil samples in freshwater for 6–8 h, then selected the cotton roots from the soil samples using a nylon mesh bag (0.1 mm-diameter pores) (Kage *et al.*, 2000; Li *et al.*, 2014). The selected roots were spread in a plastic tray, and then a flatbed image scanner (300 dpi) was used to scan the plastic tray. The Win Rhizo Pro2007 software was adopted to analyze the scanned image. The root biomass was determined by drying the selected roots in an oven at 80°C.

**Dynamics of root growth:** The dynamics of root growth was observed by the ET-100 root observation system. Minirhizotrons tubes was transparent plastic tubes installed into the rooting zone at an angle of 45° from the ground in June 2013 (Bragg *et al.*, 1983). Two Minirhizotrons tubes were installed per treatment plot (one in the cotton row, and one in the middle of inter-row). Observations were only performed once the soil surrounding the tube became stable (12 months after installation) (Jose *et al.*, 2001; Li *et al.*, 2011). The WinRhizo Tron software was adopted to analyse the images of the root observation system.

**Soil moisture:** The SWC (m$^3$ m$^{-3}$) was measured by the TRIME at intervals of 20 cm from land surface to the 100 cm soil depth every 3–5 d. The gravimetric measurements were employed to calibrate the measurement results (Weitz *et al.*, 1997). Two TRIME tubes were installed per treatment plot (one in the cotton row, and one in the middle of inter-row).

**Meteorological index:** A weather station was adopted to record the solar radiation, wind speed, humidity, air temperature and precipitation every 30 min.

## Soil Water Dynamics Modelling

**Water flow equations:** In this study, the root zone water dynamics was regarded as two-dimensional soil water flow. The equation is as follows (Richards, 1931):

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial x}\left[\mathrm{D}(\theta)\frac{\partial\theta}{\partial x}\right]+\frac{\partial}{\partial z}\left[\mathrm{D}(\theta)\frac{\partial\theta}{\partial z}\right]+\frac{\partial}{\partial z}\mathrm{K}(\theta)-\mathrm{S}(x,z,t) \quad (1)$$

Where $\theta$ is the soil water content (m$^3$ m$^{-3}$); $\mathrm{D}(\theta)$ is the unsaturated soil water diffusivity function (cm$^2$·d$^{-1}$); *x* and *z* are the transverse and vertical coordinates (cm), respectively; $\mathrm{K}(\theta)$ is the unsaturated hydraulic conductivity function (cm·d$^{-1}$); $\mathrm{S}(x, z, t)$ is the sink term (d$^{-1}$); and *t* is the number of days after transplanting (d).

Soil hydraulic properties were as follows (Genuchten, 1980):

$$\theta(h)=\begin{cases}\theta_r+(\theta_s-\theta_r)[1+|\alpha h|^n]^{-m}; & h<0\\ \theta_s; & h\geq 0\end{cases} \quad (2)$$

$$K(\theta)=K_s S_e{}^l[1-(1-S_e{}^{1/m})^m]^2 \quad (3)$$

$$S_e=\frac{(\theta-\theta_r)}{(\theta_s-\theta_r)} \quad (4)$$

$$m=1-\frac{1}{n},\ n>1 \quad (5)$$

Where $\theta_r$ is the residual water content (m$^3$·m$^{-3}$); $\theta_s$ is the saturated water content ($m^3 \cdot m^{-3}$); $\alpha$, $n$ and $m$ are the shape parameters; $K_s$ is the saturated hydraulic conductivity ($cm \cdot d^{-1}$); $S_e$ is the relative saturation; and $l$ is the pore connectivity parameter. The soil characteristic parameters are showed in Table 1.

**Initial and boundary conditions:** HYDRUS-2D was adopted to simulate the SWC from the date of transplantation until the end of bloom and boll-forming stage. The soil moisture data measured before transplanting cotton seedlings were used as the initial condition. The time-variable flux boundary condition was used at the upper boundary to represent MHI, and the lower boundary was defined as the free drainage boundary condition (Zheng *et al.*, 2017; Zeng *et al.*, 2018).

**Root water uptake:** The sink term $S(z, t)$ in Eq. (1) is defined as follows (Li *et al.*, 2015; Zhang *et al.*, 2017):

$$S(x,z,t) = \frac{á(h)\, S_t\, T_p(t)\, \mathrm{RLD}(x,z,t)}{\int_0^{X_m(t)} \int_0^{Z_m(t)} \mathrm{RLD}(x,z,t)\,dxdz} \qquad (6)$$

Where $S(x,z,t)$ is the rate of two-dimensional root water uptake ($d^{-1}$); $\alpha(h)$ is the root water uptake reduction function; $S_t$ is the soil surface width associated with transpiration (cm); $T_p(t)$ is the rate of potential transpiration (cm $d^{-1}$); $\mathrm{RLD}(x,z,t)$ is the root dynamics function (cm $cm^{-3}$); $X_m$ is the maximum horizontal extension distance of root system (cm); and $Z_m$ is the maximum root depth (cm).

A ($h$) represents the decreases of root water uptake and is calculated as follows (Feddes *et al.*, 1982):

$$á(h) = \begin{cases} 0 & h \le P3 \\ \dfrac{h - P3}{P2 - P3} & P3 < h \le P2 \\ 1 & P2 < h \le Popt \\ \dfrac{P0 - h}{P0 - Popt} & Popt < h \le P0 \\ 0 & P0 < h \le 0 \end{cases} \qquad (7)$$

Where *P0*, *Popt*, *P2* and *P3* are threshold values. Water uptake is maximal between *Popt* and *P2*, decreases linearly when $h > Popt$ or $h < P2$, and becomes zero when $h > P0$ or $h < P3$ (Feddes *et al.*, 1982). The parameters in this study were taken as: $P0 = -10$ cm, $Popt = -25$ cm, $P2 = -200$ to $-600$ cm and $P3 = -14000$ cm, respectively (Forkutsa *et al.*, 2009; Mguidiche *et al.*, 2015).

$\mathrm{RLD}(x,z,t)$ is calculated as follows (Vrugt *et al.*, 2001):

$$\mathrm{RLD}(x,z,t) = [1 - x/X_m(t)][1 - z/Z_m(t)]e^{-[P_x/X_m(t)]|x^* - x| - [P_z/Z_m(t)]|z^* - z|} \qquad (8)$$

Where $x^*$, $z^*$ (cm), $p_x$ (-) and $p_z$ (-) are empirical parameters.

**Potential transpiration and evaporation:** We calculated the daily potential transpiration and evaporation using the dual crop coefficient approach (Allen *et al.*, 2005):

$$ET_c = K_c ET_0 = (K_e + K_{cb})ET_0 \qquad (9)$$

Where $ET_c$ is the daily potential evapotranspiration (cm $d^{-1}$); $ET_0$ is the reference crop evapotranspiration (cm $d^{-1}$); $K_e$ is the soil evaporation coefficient; and $K_{cb}$ is the basal crop coefficient.

### Model Validation

The indicators evaluating the "goodness-of-fit" of the model are as follows: average absolute error (AAE); root mean square error (RMSE); model efficiency (EF) and coefficient of determination ($R^2$) (Moriasi *et al.*, 2007; Paredes *et al.*, 2014):

$$\mathrm{AAE} = \frac{1}{n}\sum_{i=1}^{n} |y_i - x_i| \qquad (10)$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n} (y_i - x_i)^2} \qquad (11)$$

$$\mathrm{EF} = 1 - \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad (12)$$

$$R^2 = \left(\frac{\sum_{i=1}^{n} (y_i - \bar{y})(x_i - \bar{x})}{\sqrt{\sum_{i=1}^{n} (y_i - \bar{y})^2}\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2}}\right)^2 \qquad (13)$$

Where $n$ is the total number of observations; $x_i$ and $y_i$ are the observed and simulated values at time $i$, respectively; $\bar{x}$ and $\bar{y}$ are the mean values of the observed and simulated data, respectively.

## Results

### Comparison of the Root Systems between Transplanted and Direct-seeded Cottons

Fig. 1 shows that transplanted cotton root was deformed compared with direct-seeded cotton root. Compared with the typical taproot system of direct-seeded cotton, the transplanted root consisted of some claw-shaped branch roots, and its taproot was degenerated despite the fact that transplanted cotton belongs to woody plant.

Fig. 2 shows the comparison of the two-dimensional RLD distributions between transplanted and direct-seeded cottons. The root system of transplanted cotton distributed in shallower soil layer (0–30 cm) than that of direct-seeded cotton. For transplanted cotton, 77% of the total root length was observed in 0–30 cm soil layer, whereas only 63% was observed in 0–30 cm soil layer for direct-seeded cotton. In 30–70 cm soil layer, the average RLD of direct-seeded cotton was 41% larger than that of transplanted cotton. The maximum RLD of transplanted cotton was 0.90 cm $cm^{-3}$, whereas that of direct-seeded was 0.72 cm $cm^{-3}$.

### Effects of Irrigation Regimes on the Spatial Distribution of the Transplanted Cotton Root

**Vertical distribution with soil depth:** Variations of RLD and RBD of transplanted cotton with soil depth under MHI with different irrigation regimes are shown in Fig. 3. The irrigation regime significantly influenced the RLD and

**Fig. 1:** Root morphologies resulting from different planting patterns (The two on the left were the direct-seeded cotton, and the two on the right were the transplanted cotton)

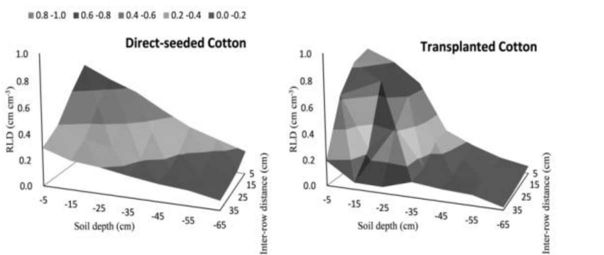


**Fig. 2:** Comparison of the two-dimensional root length density (RLD) distributions between transplanted and direct-seeded cottons

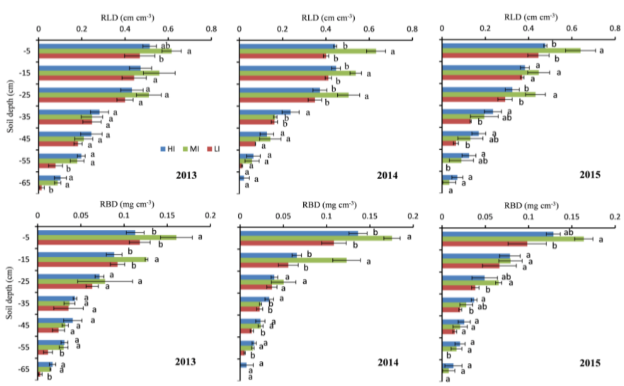


**Fig. 3:** Variations of root length density (RLD) and root biomass density (RBD) with soil layer under micro-sprinkling hose irrigation (MHI) with different irrigation regimes. Horizontal represents standard deviation. For RLD and RBD, different letters within groups indicate significant differences at $p \leq 0.05$ (Tukey's test). Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

RBD of transplanted cotton. For the depths of 0–70 cm, the average RLD in the MI treatment was 12% and 41% larger than that in the HI and LI treatment, respectively. The average RLD at 0–30 cm in the MI treatment was larger by 26% and 36% compared with HI and LI, respectively. For the depths of 30–70 cm, HI and MI significantly increased the RLD compared with LI. RBD has the similar variation compared with RLD. For the depths of 0–70 cm, the average RBD in the MI treatment was 18% and 53% larger than that in the HI and LI treatment, respectively. Compared with LI, the RBDs at the depths of 20–70 cm in the HI and MI treatment were significantly increased.

**Two-dimensional RLD distribution:** Fig. 4 shows the two-dimensional RLD distributions under MHI with different irrigation regimes. In the vertical direction, 70% to 88% of the total root length of transplanted cotton was distributed at the depths of 0–30 cm. The highest values were 0.674 cm cm$^{-3}$ in HI, 1.089 cm cm$^{-3}$ in MI, and 0.715 cm cm$^{-3}$ in LI. The highest RLDs in MI and LI were observed in the 0–10 cm soil layer, and that in HI was at depths of 10–20 cm. In the horizontal direction, most roots of transplanted cotton were concentrated in the area beneath cotton planted. 59 to 78% of the total root length of transplanted cotton was distributed in 0–20 cm inter-row distance.

## Effects of Irrigation Regimes on the Growth of the Transplanted Cotton Root

**Variations in RLD, root tip number density (RTND), root surface area density (RSAD) and root diameter (RD):** The dynamic changes of transplanted cotton root under MHI with different irrigation regimes during the experimental seasons in 2014 and 2015 are shown in Fig. 5 and 6. MI improved the RLD, RTND, RSAD and RD compared with HI and LI. On average, the RLD, RTND, RSAD and RD in the MI treatment were 21%, 30%, 32% and 8% larger than these in the HI treatment, and 67%, 77%, 74% and 19% larger than these in the LI treatment.

With the growth of transplanted cotton, RLD, RTND and RSAD increased first and then decreased, while RD increased monotonically. The largest RLD, RTND and RSAD in the MI treatment were 0.40 cm cm$^{-2}$, 0.80 tips cm$^{-2}$ and 0.035 cm$^2$ cm$^{-2}$, respectively, which were 20, 26 and 13% larger than these in the HI treatment, and 49, 28 and 36% larger than these in the LI treatment.

**RLD parameters in HYDRUS-2D:** In this study, the RLDs measured by Minirhizotrons were used to determine the root parameters in HYDRUS-2D. As the root distribution in HYDRUS-2D is assumed to be constant throughout entire plant growth period, we input the RLD parameters of transplanted cotton in Eq. (8) successively in the different growth stages. Table 3 shows the root parameters of transplanted cotton in the different growth stages.

## Simulation of Soil Water Dynamics

Hydrus-2D was calibrated to predict the root zone water dynamics. The AAEs, RMSEs, EFs and $R^2$s for the observations and simulations in 2013–2015 are presented in Table 4. On average, the AAE, RMSE, EF and $R^2$ were 0.009 m$^3$ m$^{-3}$, 0.015 m$^3$ m$^{-3}$, 0.825 and 0.839 in the HI treatment, 0.011 m$^3$ m$^{-3}$, 0.017 m$^3$ m$^{-3}$, 0.859 and 0.863 in the MI treatment, and 0.010 m$^3$ m$^{-3}$, 0.015 m$^3$ m$^{-3}$, 0.900 and 0.894 in the LI treatment, respectively. Considering

**Table 3:** The root length density (RLD) parameters of transplanted cotton in the different growth stages

| Growth Period | Treatment | $p_x$ | $p_z$ | $x^*$ | $z^*$ |
|---|---|---|---|---|---|
| Seedling stage | HI | 1.03 | 1.39 | 9.87 | 12.73 |
| | MI | 0.76 | 0.65 | 10.32 | 13.21 |
| | LI | 1.23 | 1.43 | 8.98 | 13.43 |
| Squaring stage | HI | 1.01 | 0.99 | 9.98 | 17.68 |
| | MI | 0.67 | 0.64 | 10.21 | 16.21 |
| | LI | 1.32 | 1.53 | 9.11 | 14.14 |
| Bloom and boll-forming stage | HI | 0.72 | 1.19 | 12.21 | 21.21 |
| | MI | 0.71 | 0.61 | 13.21 | 17.22 |
| | LI | 1.12 | 1.43 | 13.21 | 19.80 |
| Boll opening stage | HI | 1.02 | 1.59 | 10.21 | 19.87 |
| | MI | 0.52 | 0.55 | 11.23 | 17.32 |
| | LI | 1.33 | 1.53 | 13.21 | 18.22 |

Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

**Table 4:** Indicators for evaluating the agreement between the simulated results and the observed soil water contents

| Year | Treatment | AAE | RMSE | EF | $R^2$ |
|---|---|---|---|---|---|
| 2013 | HI | 0.010 | 0.015 | 0.858 | 0.860 |
| | MI | 0.011 | 0.018 | 0.851 | 0.868 |
| | LI | 0.012 | 0.017 | 0.898 | 0.908 |
| 2014 | HI | 0.009 | 0.013 | 0.825 | 0.840 |
| | MI | 0.010 | 0.016 | 0.876 | 0.881 |
| | LI | 0.011 | 0.016 | 0.851 | 0.870 |
| 2015 | HI | 0.009 | 0.016 | 0.793 | 0.817 |
| | MI | 0.013 | 0.018 | 0.852 | 0.840 |
| | LI | 0.007 | 0.011 | 0.950 | 0.903 |

Here AAE = average absolute error; RMSE = root mean square error; EF = model efficiency; HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

these indicators, the simulation results were good when using these root parameters.

As the similar variations of SWC were obtained during the three years, only the simulation results in 2013 are shown in the figure. Fig. 7 shows the dynamic changes of measured (dots) and simulated (lines) data. The simulation results were in close agreement with the observations in both irrigation methods. Moreover, the fluctuation tendencies of the simulated SWCs were consistent with the events of rainfall and irrigation. The amplitude of fluctuation for the SWCs in upper soil layer was larger than that in deeper soil layer. For the soil depths of 0–30 cm, the SWCs fluctuated and ranged from 0.148–0.465 $m^3$ $m^{-3}$. For the soil depths of 30–70 cm, the SWCs ranged from 0.196–0.421 $m^3$ $m^{-3}$ and their peaks lagged about 1–2 d behind those at 0–30 cm. The SWCs at depth of 90 cm were relatively stable, and they showed a single peak change during the simulated growth period.

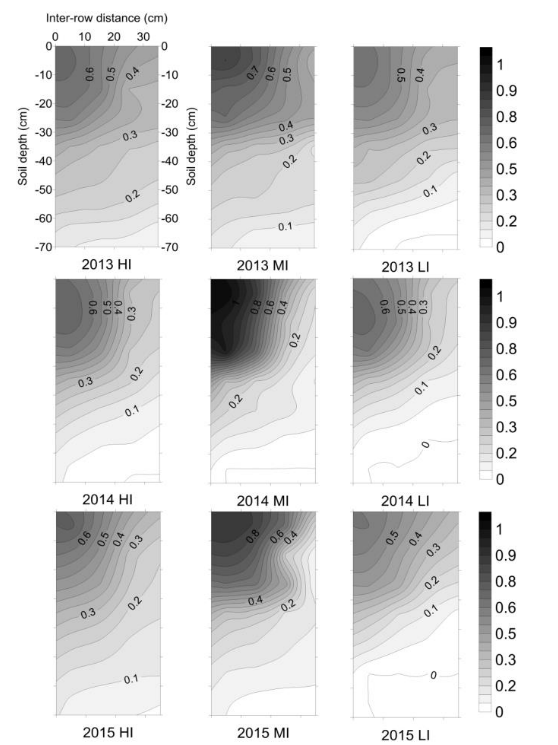


**Fig. 4:** The two-dimensional root length density (RLD, $cm^3$ $cm^{-3}$) distributions of transplanted cotton under micro-sprinkling hose irrigation (MHI) with different irrigation regimes. Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

## Discussion

The root system of cotton is affected by planting patterns (Mao *et al.*, 2008; Zhi *et al.*, 2017). Zhi *et al.* (2017) assessed the responses of cotton roots to three different cotton planting patterns, and found the rooting depths in directly sown cotton were approximately 10 cm greater than those in substrate seedling transplanted cotton and soil-cube seedling transplanted cotton. In this study, the transplanted cotton root was deformed compared with direct-seeded cotton root (Fig. 1), and this phenomenon was attributed to

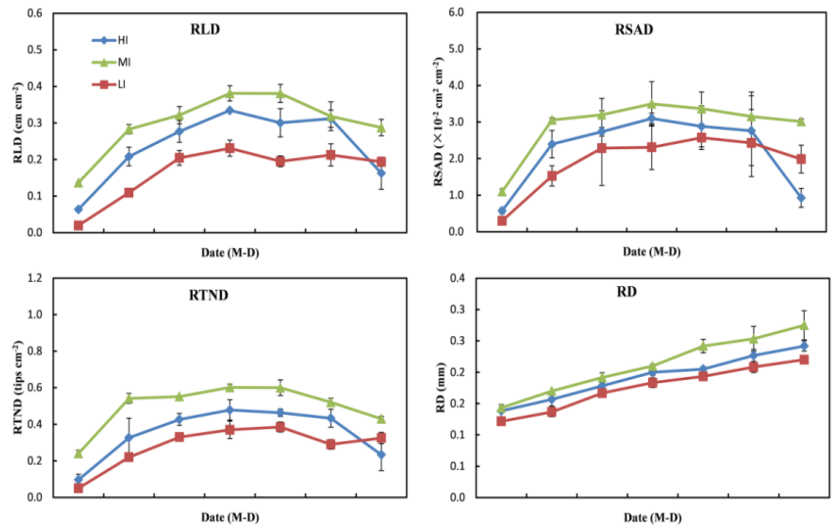


**Fig. 5:** Changes in root length density (RLD), root surface area density (RSAD), root tip number density (RTND) and root diameter (RD) under micro-sprinkling hose irrigation (MHI) with different irrigation regimes during the experimental seasons in 2014. Vertical represents standard deviation. Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

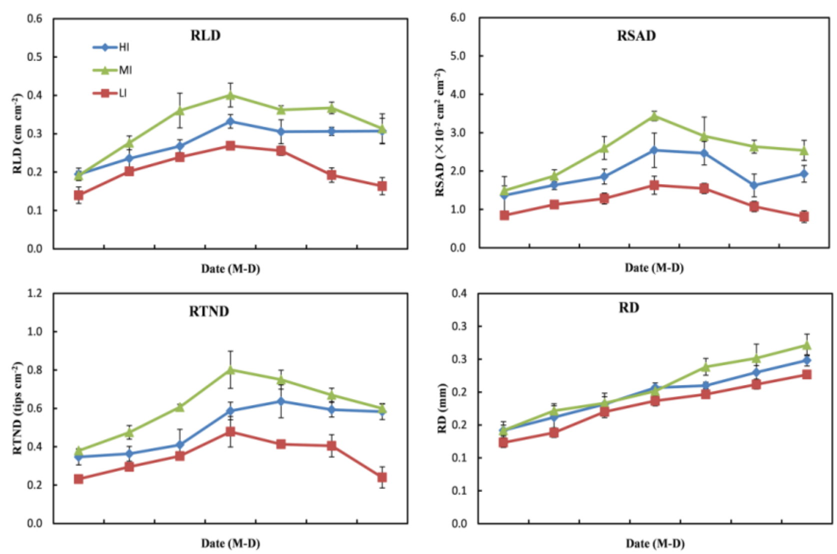


**Fig. 6:** Changes in root length density (RLD), root surface area density (RSAD), root tip number density (RTND) and root diameter (RD) under micro-sprinkling hose irrigation (MHI) with different irrigation regimes during the experimental seasons in 2015. Vertical represents standard deviation. Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

that the transplanted cotton root was distorted from binding of the cotton plug-seedling before transplantation. Results in the Experiment 1 also showed that the root system of transplanted cotton was distributed in shallower soil layer (0–30 cm) than that of direct-seeded cotton (Fig. 2). This was due to that the distortion made cotton root lose the advantage of taproot after transplanting into the field, whereas promoted the growth of lateral roots. The growth direction of lateral roots changed from horizontal direction to oblique downward direction (Fig. 1). Our experimental result on the transplanted cotton root was same with Mao *et al.* (2008), who made preliminary observations on the transplanted and direct-seeded cotton root.

The distorted roots of transplanted cotton were affected by the irrigation regime under MHI. In this study, HI was irrigated to replace depleted water and the other two treatments were managed with different levels of deficit irrigation. Sampathkumar *et al.* (2013) study the effect of deficit irrigation practices on the soil moisture distribution and the root growth in cotton–maize cropping sequence; he

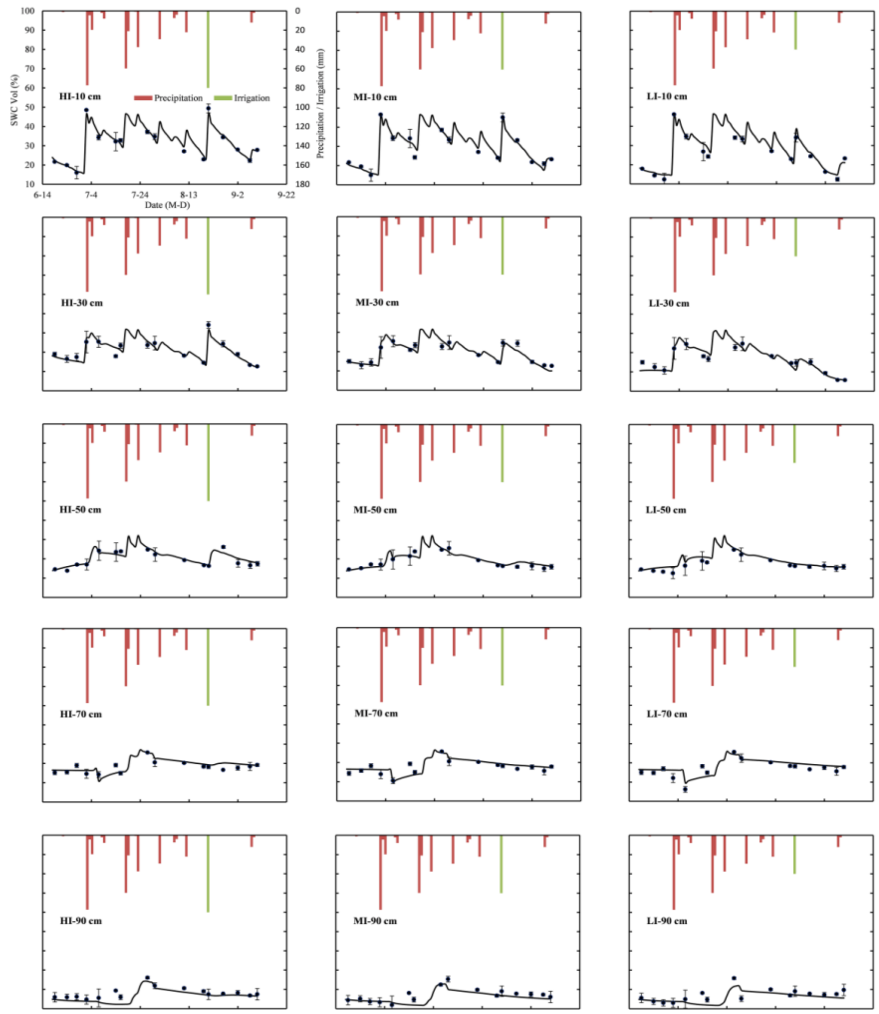


**Fig. 7:** Simulated soil water contents (SWCs, lines) and measured SWCs (dots) under micro-sprinkling hose irrigation (MHI) with different irrigation regimes in 2013. Vertical represents standard deviation. Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm)

found the mild deficit irrigation produced longer lateral roots from both the sides of the plant, and severe water stress affected the lateral root spread and recorded lower values than other irrigation treatments. This was consistent with our experimental results. In our study, both soil core method and Minirhizotrons showed that the transplanted cotton root in the MI treatment was more developed than that in the HI and LI treatment (Fig. 3–6). However, Rao *et al.* (2016) investigate the effect of deficit irrigation through drip irrigation on root growth of cotton, and found severe water stressed plants (0.6 $ET_c$) produced longer but thinner roots compared to fully watered (1.0 $ET_c$) and mild stressed treatments (0.8 $ET_c$). In fact, deficit irrigation affects cotton root growth mainly by controlling the SWC. In the study of Hu *et al.* (2009), the weight of cotton root was the highest and its growth was also the fastest when the SWC in the root zone was near 75% of field capacity; when the SWC was near 90% or 60% of field capacity, the cotton root grew slowly. In this study, the SWCs in the MI treatment were closer to 75% of field capacity compared with those in the HI and LI treatment (Fig. 7). The large irrigation quota in the HI treatment reduced the number of unsaturated soil pores, the root respiration was easy to be obstructed (Yu *et al.*, 2015). Whereas, the irrigation quota in the LI treatment was so small that it affected the metabolism of root cells (Kim *et al.*, 2017; Wang *et al.*, 2017). So the SWC in the MI treatment was the suitable soil water condition, and were beneficial to the root growth.

The simulation of root zone water dynamics is one of the important applications for root research (Ning *et al.*, 2015; Jha *et al.*, 2017). The root data measured in the experiment can be used to determine the root parameters in HYDRUS-2D which is widely applied to simulate soil water dynamics in recent years (Kandelous and ŠImůNek, 2010; Bufon *et al.*, 2012; Han *et al.*, 2015; Li *et al.*, 2015). Han *et al.* (2015) used the HYDRUS-2D model to simulate the soil water dynamics of cotton under different irrigation amounts, and indicated that the observed SWCs and the simulated results obtained with HYDRUS-2D are in good agreement. In the study of Li *et al.* (2015), HYDRUS-2D model also described different irrigation events and SWCs in the root zone well. Kandelous and ŠImůNek (2010), Bufon *et al.* (2012) have the similar opinions. However, due to the limitation of the HYDRUS-2D, the root distribution was considered to be constant in their entire simulation process. In our study, the RLD parameters of transplanted cotton were input successively in the different growth stages to deal with the limitation of the HYDRUS-2D (Table 3). The simulation results were in close agreement with the observations (Table 4 and Fig. 7). The AAEs, RMSEs, EFs and $R^2$s were in the range and better than many research results (Xi *et al.*, 2016; Jha *et al.*, 2017; Zheng *et al.*, 2017). The amplitude of fluctuation for the SWCs at depth of 0–30 cm was larger than that at depth of 30–90 cm (Fig. 7), and this phenomenon was attributed to that the precipitation, irrigation, evaporation and transpiration mainly affect the 0–30 cm soil layer (Bufon *et al.*, 2012; Han *et al.*, 2015). Due to the frequent, continuous and heavy rainfall in 2013, the SWCs of any soil layers in 2013 were all higher than those during the same time in 2014 and 2015 (Fig. 7). The leakage losses of irrigation water and soluble nutrients can be minimized by calculating the vertical wetting front advance with HYDRUS-2D model (Elmaloglou and Diamantopoulos, 2013). This simulation study is helpful for improving irrigation water use efficiency and optimizing irrigation strategies for the transplanted cotton fields under MHI (Patel and Rajput, 2008; Elmaloglou and Diamantopoulos, 2013; Li *et al.*, 2015).

## Conclusion

The main conclusions of this study are as follows: (i) the transplanted cotton root was distorted from binding of the cotton plug-seedling before transplantation, and was distributed in shallower soil layer (0–30 cm) than direct-seeded cotton root; (ii) compared with irrigation quotas of 80 mm and 40 mm, MHI with 60 mm irrigation quota could promote the root development of transplanted cotton, and was the recommended irrigation mode for transplanted cotton; (iii) the SWCs simulated by HYDRUS-2D model were in close agreement with the observations in transplanted cotton field under MHI; therefore, the irrigation schedule in transplanted cotton field can be formulated according to the simulation results by HYDRUS-2D model.

## Acknowledgements

We acknowledge financial support from the Science and Technology Special Project in Henan Province (82102310049) and the National Modern Agricultural Cotton Industry Technology System of China (CARS-15-13).

## References

Allen, R.G., M. Smith, J.L. Wright, D. Raes and L.S. Pereira, 2005. FAO-56 Dual Crop Coefficient Method for Estimating Evaporation from Soil and Application Extensions. *J. Irrig. Drain. Eng.*, 131: 2–13

Bragg, P.L., G. Govi and R.Q. Cannell, 1983. A comparison of methods, including angled and vertical minirhizotrons, for studying root growth and distribution in a spring oat crop. *Plant Soil*, 73: 435–440

Bufon, V.B., R.J. Lascano, C. Bednarz, J.D. Booker and D.C. Gitz, 2012. Soil water content on drip irrigated cotton: comparison of measured and simulated values obtained with the Hydrus 2-D model. *Irrig. Sci.*, 30: 259–273

CRI (Cotton Research Institute Chinese Academy of Agricultural Sciences), 2013. *Cultivation of Cotton in China*, 1st edition, Shanghai Science and Technology Press, Shanghai, China

Dai, J.L. and H.Z. Dong, 2014. Intensive cotton farming technologies in China: Achievements, challenges and countermeasures. *Field Crops Res.*, 155: 99–110

Dong, H.Z., W.J. Li, W. Tang, Z.H. Li and D.M. Zhang, 2007. Enhanced plant growth, development and fiber yield of *Bt* transgenic cotton by an integration of plastic mulching and seedling transplanting. *Ind. Crops Prod.*, 26: 298–306

Dong, H.Z., W.J. Li, W. Tang, Z.H. Li, D.W. Zhang and Y.H. Niu, 2006. Yield, quality and leaf senescence of cotton grown at varying planting dates and plant densities in the Yellow River Valley of China. *Field Crops Res.*, 98: 106–115

Dong, H.Z., W.J. Li, W. Tang, Z.H. Li and D.H. Zhang, 2005. Increased yield and revenue with a seedling transplanting system for hybrid seed production in *Bt* cotton. *J. Agron. Crop Sci.*, 191: 116–124

Elmaloglou, S. and E. Diamantopoulos, 2013. Simulation of soil water dynamics under subsurface drip irrigation from line sources. *Water Resour. Manage.*, 27: 4131–4148

Feddes, R.A., P.J. Kowalik and H. Zaradny, 1982. Simulation of field water use and crop yield. *Soil Sci.*, 129: 193

Forkutsa, I., R. Sommer, Y.L. Shirokova, J.P.A. Lamers, K. Kienzler, B. Tischbein, C. Martius and P.L.G. Vlek, 2009. Modeling irrigated cotton with shallow groundwater in the Aral Sea Basin of Uzbekistan: II. Soil salinity dynamics. *Irrig. Sci.*, 27: 319–330

Genuchten, M.T.V., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Amer. J.*, 44: 892–898

Han, M., C.Y. Zhao, G. Feng, Y.Y. Yan and Y. Sheng, 2015. Evaluating the Effects of Mulch and Irrigation Amount on Soil Water Distribution and Root Zone Water Balance Using HYDRUS-2D. *Water*, 7: 2622–2640

Hu, X.T., H. Chen, J. Wang, X.B. Meng and F.H. Chen, 2009. Effects of Soil Water Content on Cotton Root Growth and Distribution Under Mulched Drip Irrigation. *Agric. Sci. Chin.*, 8: 709–716

Hulugalle, N.R., K.J. Broughton and D.K.Y. Tan, 2015. Fine root production and mortality in irrigated cotton, maize and sorghum sown in vertisols of northern New South Wales, Australia. *Soil Till. Res.*, 146: 313–322

Jha, S.K., Y. Gao, H. Liu, Z.D. Huang, G.S. Wang, Y.P. Liang and A.W. Duan, 2017. Root development and water uptake in winter wheat under different irrigation methods and scheduling for North China. *Agric. Water Manage.*, 182: 139–150

Jose, S., A.R. Gillespie, J.R. Seifert and P.E. Pope, 2001. Comparison of minirhizotron and soil core methods for quantifying root biomass in a temperate alley cropping system. *Agrofor. Syst.*, 52: 161–168

Kage, H., M. Kochler and H. Stutzel, 2000. Root growth of cauliflower (*Brassica oleracea* L. botrytis) under unstressed conditions: measurement and modelling. *Plant Soil*, 223: 131–145

Kandelous, M.M. and J. ŠImůNek, 2010. Numerical simulations of water movement in a subsurface drip irrigation system under field and laboratory conditions using HYDRUS-2D. *Agric. Water Manage.*, 97: 1070–1076

Kandelous, M.M., J. Šimůnek, M.T.V. Genuchten and K. Malek, 2011. Soil Water Content Distributions between Two Emitters of a Subsurface Drip Irrigation System. *Soil Sci. Soc. Amer. J.*, 75: 488–497

Kim, J.M., T.K. To, A. Matsui, K. Tanoi, N. Kobayashi, F. Matsuda, Y. Habu, D. Ogawa, T. Sakamoto, S. Matsunaga, K. Bashir, S. Rasheed, M. Ando, H. Takeda, K. Kawaura, M. Kusano, A. Fukushima, T.A. Endo, T. Kuromori, J. Ishida, T. Morosawa, M. Tanaka, C. Torii, Y. Takebayashi, H. Sakakibara, Y. Ogihara, K. Saito, K. Shonozaki, A. Devoto and M. Seki, 2017. Acetate-mediated novel survival strategy against drought in plants. *Nat. Plants*, 3: 17097

Li, C.X., X.G. Zhou, J.S. Sun, H.Z. Wang and Y. Gao, 2014. Dynamics of root water uptake and water use efficiency under alternate partial root-zone irrigation. *Desalin. Water Treat.,* 52: 2805–2810

Li, C.X., J.S. Sun, F.S. Li, X.G. Zhou, Z.Y. Li, X.M. Qiang and D.D. Guo, 2011. Response of root morphology and distribution in maize to alternate furrow irrigation. *Agric. Water Manage.,* 98: 1789–1798

Li, X.Y., H.B. Shi, J. Šimůnek, X.W. Gong and Z.Y. Peng, 2015. Modeling soil water dynamics in a drip-irrigated intercropping field under plastic mulch. *Irrig. Sci.,* 33: 289–302

Li, Y., J. Šimunek, S. Wang, J. Yuan and W. Zhang, 2017. Modeling of Soil Water Regime and Water Balance in a Transplanted Rice Field Experiment with Reduced Irrigation. *Water,* 9: 248

Liu, H., Y. Gao, J.S. Sun, X.L. Wu, S.K. Jha, H. Zhang, X.W. Gong and Y. Li, 2017. Responses of yield, water use efficiency and quality of short-season cotton to irrigation management: interactive effects of irrigation methods and deficit irrigation. *Irrig. Sci.,* 35: 125–139

Luo, H.H., Y.L. Zhang and W.F. Zhang, 2016. Effects of water stress and rewatering on photosynthesis, root activity, and yield of cotton with drip irrigation under mulch. *Photosynthetica*, 54: 65–73

Luo, H.H., X.P. Tao, Y.Y. Hu, Y.L. Zhang and W.F. Zhang, 2015. Response of cotton root growth and yield to root restriction under various water and nitrogen regimes. *J. Plant Nutr. Soil Sci.,* 178: 384–392

Ma, Q.X., Z.Y. Wang, X.W. Cui, J.J. Hao and X.Y. Du, 2010. Comparison of comprehensive benefit between cotton transplanting and wheat cotton interplanting. *J. Henan Agric. Sci.,* 39: 26–27

Man, J.G., J.S. Yu, P.J. White, S.B. Gu, Y.L. Zhang, Q.F. Guo, Y. Shi and D. Wang, 2014. Effects of supplemental irrigation with micro-sprinkling hoses on water distribution in soil and grain yield of winter wheat. *Field Crops Res.,* 161: 26–37

Mao, S.C., P.C. Li, Y.C. Han, G.P. Wang, Y.B. Li and X.H. Wang, 2008. Preliminary Observation on Morphological Parameters of Root System of the Root-naked Transplanting Cotton (*Gossypium hirsutum* L.). *Cott. Sci.,* 20: 76–78

Mguidiche, A., G. Provenzano, B. Douh, S. Khila, G. Rallo and A. Boujelben, 2015. Assessing Hydrus-2D to Simulate Soil Water Content (SWC) and Salt Accumulation Under an SDI System: Application to a Potato Crop in a Semi-Arid Area of Central Tunisia. *Irrig. Drain.,* 64: 263–274

Min, W., H.J. Guo, G.W. Zhou, W. Zhang, L.J. Ma, J. Ye and Z.N. Hou, 2014. Root distribution and growth of cotton as affected by drip irrigation with saline water. *Field Crops Res.,* 169: 1–10

Moriasi, D.N., J.G. Arnold, M.W.V. Liew, R.L. Bingner, R.D. Harmel and T.L. Veith, 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. Asabe,* 50: 885–900

Ning, S.R., J.C. Shi, Q. Zuo, S. Wang and A. Ben-Gal, 2015. Generalization of the root length density distribution of cotton under film mulched drip irrigation. *Field Crops Res.,* 177: 125–136

Paredes, P., J.P.D. Melo-Abreu, I. Alves and L.S. Pereira, 2014. Assessing the performance of the FAO AquaCrop model to estimate maize yields and water use under full and deficit irrigation with focus on model parameterization. *Agric. Water Manage.,* 144: 81–97

Patel, N. and T.B.S. Rajput, 2008. Dynamics and modeling of soil water under subsurface drip irrigated onion. *Agric. Water Manage.,* 95: 1335–1349

Phogat, V., M. Mahadevan, M. Skewes and J.W. Cox, 2012. Modelling soil water and salt dynamics under pulsed and continuous surface drip irrigation of almond and implications of system design. *Irrig. Sci.,* 30: 315–333

Rao, S.S., S.P.S. Tanwar and P.L. Regar, 2016. Effect of deficit irrigation, phosphorous inoculation and cycocel spray on root growth, seed cotton yield and water productivity of drip irrigated cotton in arid environment. *Agric. Water Manage.,* 169: 14–25

Richards, L.A., 1931. Capillary conduction of liguids through porous mediums. *Physics,* 1: 318–333

Salgado, E. and R. Cautín, 2008. Avocado root distribution in fine and coarse-textured soils under drip and microsprinkler irrigation. *Agric. Water Manage.,* 95: 817–824

Sampathkumar, T., B.J. Pandian, M.V. Rangaswamy, P. Manickasundaram and P. Jeyakumar, 2013. Influence of deficit irrigation on growth, yield and yield parameters of cotton–maize cropping sequence. *Agric. Water Manage.,* 130: 90–102

Shah, M.A., M. Farooq and M. Hussain, 2017. Evaluation of transplanting *bt* cotton in a cotton-wheat cropping system. *Exp. Agric.,* 53: 227–241

Vrugt, J.A., M.T.V. Wijk, J.W. Hopmans and J. Simunek, 2001. One-, two-, and three-dimensional root water uptake functions for transient modeling. *Water Resour. Res.,* 37: 2457–2470

Wang, S., R.M. Callaway, D.W. Zhou and J. Weiner, 2017. Experience of inundation or drought alters the responses of plants to subsequent water conditions. *J. Ecol.,* 105: 176–187

Weitz, A.M., W.T. Grauel, M. Keller and E. Veldkamp, 1997. Calibration of time domain reflectometry technique using undisturbed soil samples from humid tropical soils of volcanic origin. *Water Resour. Res.,* 33: 1241–1249

Xi, B., M. Bloomberg, M.S. Watt, Y. Wang and L. Jia, 2016. Modeling growth response to soil water availability simulated by HYDRUS for a mature triploid *Populus tomentosa* plantation located on the North China Plain. *Agric. Water Manage.,* 176: 243–254

Yu, Y.X., C.Y. Zhao, Z.M. Zhao, B. Yu and T.H. Zhou, 2015. Soil respiration and the contribution of root respiration of cotton (*Gossypium hirsutum* L.) in arid region. *Acta Ecol. Sin.,* 35: 17–21

Zeng, W., G. Lei, Y. Zha, Y. Fang, J. Wu and J. Huang 2018. Sensitivity and uncertainty analysis of the HYDRUS-1D model for root water uptake in saline soils. *Crop Pasture Sci.,* 69: 163–173

Zhang, H., H. Liu, C.T. Sun, Y. Gao, X.W. Gong, J.S. Sun and W.N. Wang, 2017. Root development of transplanted cotton and simulation of soil water movement under different irrigation methods. *Water*, 9: 503

Zhang, L., W.V.D. Werf, L. Bastiaans, S. Zhang, B. Li and J.H.J. Spiertz, 2008. Light interception and utilization in relay intercrops of wheat and cotton. *Field Crops Res.,* 107: 29–42

Zhang, L., W.V.D. Werf, S. Zhang, B. Li and J.H.J. Spiertz, 2007. Growth, yield and quality of wheat and cotton in relay strip intercropping systems. *Field Crops Res.,* 103: 178–188

Zhang, X.J., Z.W. Wu, X.M. Ding and X. Li, 2009. Experimental analysis of water distribution characteristics of micro-sprinkling hose. *Trans. Chin. Soc. Agric. Eng.,* 25: 66–69

Zheng, C., Y.D. Lu, X.H. Guo, H.H. Li, J.M. Sai and X.H. Liu, 2017. Application of HYDRUS-1D model for research on irrigation infiltration characteristics in arid oasis of northwest China. *Environ. Earth Sci.,* 76: 785

Zhi, X.Y., Y.C. Han, Y.B. Li, G.P. Wang, L. Feng, B.F. Yang, Z.Y. Fan, Y.P. Lei, W.L. Du and S.C. Mao, 2017. Root growth and spatial distribution characteristics for seedlings raised in substrate and transplanted cotton. *Plos One,* 12: e0190032

**(Received 12 July 2018; Accepted 28 August 2018)**