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

Hao Zhang1, Hao Liu2, Shunsheng Wang1, Xuan Guo1, Xuewen Gong1 and Jingsheng Sun2*

1School of Water Conservancy, North China University of Water Resources and Electric Power, Zhengzhou 450046, China
2Key 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 $R^2$ 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. © 2018 Friends Science Publishers

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 sufficient 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., 2012, 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 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 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 (Bulon et al., 2012; Elmaloglu 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 (Kundelous 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 bolts were picked by hand two times each season. The first picking was conducted when approximately 50% of the bolts opened. The last picking was conducted when the remaining bolts 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%), medium irrigation (MI, 60%) and low irrigation (LI, 40%). 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 m³ 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.
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 (Salcedo 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 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 were 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 analyze the images of the root observation system.

**Soil moisture:** The SWC (m³ 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 was 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):

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

Where \( \theta \) is the soil water content (m³ m⁻³); \( D(\theta) \) is the unsaturated soil water diffusivity function (cm² d⁻¹); \( x \) and \( z \) are the transverse and vertical coordinates (cm), respectively; \( K(\theta) \) is the unsaturated hydraulic conductivity function (cm d⁻¹); \( S(x, z, t) \) is the sink term (d⁻¹); and \( t \) is the number of days after transplanting (d).

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

\[
\theta(\psi) = \left\{ \begin{align*}
\theta_s + (\theta - \theta_s)(1+|\alpha h|^{n})^{-1} & , \quad h < 0 \\
\theta_s & , \quad h \geq 0
\end{align*} \right.
\]

\[
K(\theta) = K_s \left[ 1 - \left(1 - \left(\theta - \theta_s\right) / \theta_s \right)^n \right]^{2} \quad (3)
\]

\[
S_e = \frac{(\theta - \theta_s)}{(\theta_s - \theta_s)} \quad (4)
\]

\[
m = 1 - \frac{1}{n}, \quad n>1
\]

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

<table>
<thead>
<tr>
<th>Soil layer (cm)</th>
<th>0-20</th>
<th>20-40</th>
<th>40-60</th>
<th>60-80</th>
<th>80-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture</td>
<td>Loam</td>
<td>silt loam</td>
<td>silt loam</td>
<td>silt loam</td>
<td>sandy loam</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>4</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Silt (%)</td>
<td>43</td>
<td>45</td>
<td>48</td>
<td>47</td>
<td>17</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>53</td>
<td>48</td>
<td>46</td>
<td>48</td>
<td>81</td>
</tr>
<tr>
<td>Bulk density (Mg m⁻³)</td>
<td>1.56</td>
<td>1.58</td>
<td>1.54</td>
<td>1.42</td>
<td>1.45</td>
</tr>
<tr>
<td>Field capacity (m³ m⁻³)</td>
<td>0.34</td>
<td>0.31</td>
<td>0.33</td>
<td>0.28</td>
<td>0.29</td>
</tr>
<tr>
<td>( \theta_s ) (m³ m⁻³)</td>
<td>0.127</td>
<td>0.096</td>
<td>0.095</td>
<td>0.107</td>
<td>0.066</td>
</tr>
<tr>
<td>( \theta_t ) (m³ m⁻³)</td>
<td>0.467</td>
<td>0.417</td>
<td>0.424</td>
<td>0.487</td>
<td>0.501</td>
</tr>
<tr>
<td>( K_s ) (cm d⁻¹)</td>
<td>27.6</td>
<td>9.7</td>
<td>4.7</td>
<td>12.6</td>
<td>84.7</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.012</td>
<td>0.017</td>
<td>0.022</td>
<td>0.099</td>
<td>0.012</td>
</tr>
<tr>
<td>( N )</td>
<td>1.54</td>
<td>1.31</td>
<td>1.21</td>
<td>1.46</td>
<td>1.88</td>
</tr>
<tr>
<td>( L )</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>

**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 \( \theta_t, \alpha \) and \( n \) were estimated through inverse simulation.

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Precipitation (mm)</th>
<th>Irrigation amount (mm)</th>
<th>Irrigation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>319.5</td>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>2014</td>
<td>450.2</td>
<td>160</td>
<td>80</td>
</tr>
<tr>
<td>2015</td>
<td>211.7</td>
<td>240</td>
<td>120</td>
</tr>
</tbody>
</table>

Here HI = high irrigation (80 mm); MI = medium irrigation (60 mm); and LI = low irrigation (40 mm).
Where $\theta_r$ is the residual water content (m$^3$·m$^{-3}$); $\theta_s$ is the saturated water content (m$^3$·m$^{-3}$); $a$, $n$ and $m$ are the shape parameters; $K_r$ is the saturated hydraulic conductivity (cm·d$^{-1}$); $S_r$ 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 $S(x,t)$ in Eqs. (1) is defined as follows (Li et al., 2015; Zhang et al., 2017):

$$S(x,z,t) = \frac{\alpha(h) S_r P_t(t) RLD(x,z,t)}{\int_{x_0(t)}^{x_m(t)} RLD(x,z,t) \, dx \, dz}$$

(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; $S_r$ is the soil surface width associated with transpiration (cm); $P_t(t)$ is the rate of potential transpiration (cm d$^{-1}$); $RLD(x,z,t)$ is the root dynamics function (cm cm$^{-1}$); $x_m$ is the maximum horizontal extension distance of root system (cm); and $z_m$ is the maximum root depth (cm).

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

$$\alpha(h) = \begin{cases} 
0 & h \leq P3 \\
2 - P2 & P2 < h \leq Popt \\
1 & Popt < h \leq P0 \\
0 & P0 < h < 0 
\end{cases}$$

(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).

**RLD(x,z,t) is calculated as follows (Vrugt et al., 2001):**

$$RLD(x,z,t) = \left[1 - x/R_m(t) \right] \left[1 - z/Z_m(t) \right] e^{-[P_r/S_r(t)][x^*-x] - [P_r/Z_m(t)][z^*-z]}$$

(8)

Where $x^*$, $z^*$ (cm), $p_r$ (-) 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):

$$ET_v = K_v ET_0 = (K_c + K_{cb}) ET_0$$

(9)

Where $ET_v$ is the daily potential evapotranspiration (cm d$^{-1}$); $ET_0$ is the reference crop evapotranspiration (cm d$^{-1}$); $K_c$ 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):

$$AAE = \frac{1}{n} \sum_{i=1}^{n} \left| y_i - x_i \right|$$

(10)

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

(11)

$$\text{EF} = 1 - \frac{\sum_{i=1}^{n} (y_i - x_i)^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

(12)

$$R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}$$

(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$^{-1}$, whereas that of direct-seeded was 0.72 cm cm$^{-1}$.

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

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

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

<table>
<thead>
<tr>
<th>Year</th>
<th>Treatment</th>
<th>AAE</th>
<th>RMSE</th>
<th>EF</th>
<th>( R^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013</td>
<td>HI</td>
<td>0.010</td>
<td>0.015</td>
<td>0.858</td>
<td>0.860</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>0.011</td>
<td>0.018</td>
<td>0.851</td>
<td>0.868</td>
</tr>
<tr>
<td></td>
<td>LI</td>
<td>0.012</td>
<td>0.017</td>
<td>0.895</td>
<td>0.908</td>
</tr>
<tr>
<td>2014</td>
<td>HI</td>
<td>0.009</td>
<td>0.013</td>
<td>0.825</td>
<td>0.860</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>0.010</td>
<td>0.016</td>
<td>0.876</td>
<td>0.881</td>
</tr>
<tr>
<td></td>
<td>LI</td>
<td>0.011</td>
<td>0.016</td>
<td>0.851</td>
<td>0.870</td>
</tr>
<tr>
<td>2015</td>
<td>HI</td>
<td>0.009</td>
<td>0.016</td>
<td>0.793</td>
<td>0.817</td>
</tr>
<tr>
<td></td>
<td>MI</td>
<td>0.013</td>
<td>0.018</td>
<td>0.852</td>
<td>0.840</td>
</tr>
<tr>
<td></td>
<td>LI</td>
<td>0.007</td>
<td>0.011</td>
<td>0.950</td>
<td>0.903</td>
</tr>
</tbody>
</table>

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)

0.009 m³ m⁻³, 0.015 m³ m⁻³, 0.825 and 0.839 in the HI treatment, 0.011 m³ m⁻³, 0.017 m³ m⁻³, 0.859 and 0.863 in the MI treatment, and 0.010 m³ m⁻³, 0.015 m³ m⁻³, 0.900 and 0.894 in the LI treatment, respectively. Considering 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 m³ m⁻³. For the soil depths of 30-70 cm, the SWCs ranged from 0.196-0.421 m³ 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.

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 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 so as to replace depleted water and the other two treatments were managed with different levels of deficit irrigation. Sampathkumar et al. (2013) study the

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)
effect of deficit irrigation practices on the soil moisture distribution and the root growth in cotton–maize cropping sequence; he 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

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)
water dynamics in recent years (Kandelous and ŠíměNek, 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 ŠíměNek (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 R²s 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

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

Received 12 July 2018; Accepted 28 August 2018