Modeling root growth and the soil–plant–atmosphere continuum of cotton crops

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Accepted 21 October 2002

Abstract

A simple and functional model to simulate cotton root growth is coupled to models of water balance and leaf water potential to predict the behavior of the soil–plant–atmosphere continuum (SPAC) of cotton crops. The root-growth model takes into account the dry matter partitioning to roots, root depth increase as a function of thermal time, soil mechanical resistance and soil water stress, and allows the inclusion of spatial variability of soil physical properties. The water balance model uses a cascade approach to simulate drainage while soil and plant evaporation are calculated separately following the model of Ritchie. The leaf water potential model (LWPM) is based on Ohm’s Law analogy, where water flow resistance to the roots is calculated using an empirical equation and the resistance within the plant is calculated as a function of a threshold leaf water potential. The model simulated correctly the soil resistance and the temporal and spatial distribution of roots in the soil profile. The model simulated total soil water content and midday leaf water potential well, even when a compacted soil layer was present, but the agreement to observed data was poor for the vertical distribution of soil water content, mainly in the zone of greatest root concentration.  

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Keywords: Roots; Water balance; Leaf water potential; Models; Cotton

1. Introduction

Crop growth and yield simulation models require a sub-model of root growth that should contain an adequate description of the root system by considering its growth

Abbreviations: C, compacted treatment; DAE, days after emergency; LAI, leaf area index; NC, non-compact ed treatment; RMSE, root mean square error; T1, early water stress treatment; T2, mid season water stress treatment; T3, late stress treatment; T4, well irrigated control treatment  
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Nomenclature

\( \Delta \text{BM}_{\text{root}} \) daily amount of dry matter allocated to roots (g m\(^{-2}\) per day)

\( \Delta \text{BM}_{\text{shoot}} \) shoot growth rate (g m\(^{-2}\) per day)

\( d_i \) depth down to the center of the layer \( i \) (cm)

\( \text{EEQ} \) equilibrium evaporation rate (mm per day)

\( \text{ET}_{\text{max}} \) maximum crop evapotranspiration (mm per day)

\( \text{ET}_{\text{max}}' \) intermediate variable

\( f_a \) 0–1 soil water deficit factor

\( f_r \) 0–1 soil resistance factor

\( f_s \) 0–1 stress factor

\( F \) evapotranspiration correction factor

\( F_i \) intermediate variable

\( \text{FW}_i \) fraction of total soil water present in layer \( i \)

\( i \) each of the \( m \) soil layers

\( \text{LAI}_{\text{max}} \) maximum value of LAI

\( L_v \) root length density (cm cm\(^{-3}\))

\( \Delta L_v_i \) root density increment per each \( i \) layer (cm cm\(^{-3}\))

\( m \) number of soil layers

\( n \) number of data points

\( \text{PR} \) penetrometer resistance (MPa)

\( r^2 \) correlation coefficient

\( r_{es} \) water flow resistance in stress condition (MPa mm\(^{-1}\) per day)

\( r_{ns} \) water flow resistance in no stress condition (MPa mm\(^{-1}\) per day)

\( r_t \) water flow resistance within the roots (MPa mm\(^{-1}\) per day)

\( r_s \) water flow resistance surrounding the roots (MPa mm\(^{-1}\) per day)

\( r_x \) water flow resistance in the xylem (MPa mm\(^{-1}\) per day)

\( \text{RD} \) total root depth in the profile (cm)

\( \Delta \text{RD} \) potential daily root depth increase (cm per day)

\( \text{RDF}_i \) root distribution factor for layer \( i \)

\( \text{RD}_i \) root depth in the layer \( i \) (cm)

\( \Delta \text{RL} \) total root length increment (cm m\(^{-2}\) per day)

\( \Delta \text{RL}_i \) root length increment for layer \( i \)

\( \text{SWD}_{fn} \) 0–1 soil water extraction factor

\( \text{SWD}_{w} \) soil water deficit weighted to root distribution (0–1)

\( t_{\text{max}} \) maximum temperature (°C)

\( T \) transpiration (mm per day)

\( T_{\text{max}} \) maximum transpiration (mm per day)

\( \text{TT} \) thermal time (°C per day)

\( z_i \) thickness of layer \( i \)

Greek letters

\( v \) length of 1 g of roots (cm g\(^{-1}\))

\( \theta \) total soil water content (cm\(^3\) cm\(^{-3}\))
and interactions with shoot growth and the soil environment (Klepper and Rickman, 1990).

Several mathematical models of root growth have been developed over the last 30 years. The simplest models (Gerwitz and Page, 1974; Stone and Taylor, 1983) simulated only rooting depth. A more complex generation of models simulated a root system exploring the soil in two separated processes: downward penetration of the vertical axis and horizontal proliferation of roots into individual layers (Ritchie et al., 1985; Jones and Kiniry, 1986; Andrew, 1987; Jones et al., 1991; Robertson et al., 1993).

The main soil stress factors considered by these models are: water stress (Huck and Hillel, 1983; Ritchie et al., 1985), soil mechanical resistance (Andrew, 1987; Robertson et al., 1993) and soil aeration (Penning de Vries et al., 1989; Pfeil et al., 1992). Some models consider all these stress factors (Jones et al., 1991; Grant, 1993).

These semi-mechanistic models are of restricted use, however, because they need a great number of parameters not always available or difficult to obtain. On the other hand, simple root-growth models do not consider the stress factors that reduce root growth, nor proliferation of roots into the soil layers. Both types of models have, however, ignored the spatial variability of the soil physical properties that has been identified by several researchers (Cassel, 1982; Ehlers et al., 1983) as the possible cause of unexpected observations when root growth has been related to average values of soil properties. In the case of cotton root growth, Coelho et al. (2000) found a large spatial variability in both bulk density and soil penetration resistance, which allowed roots to penetrate a subsoil compacted layer.

Although not exactly analogous, comparisons between the soil–plant–atmosphere continuum (SPAC) and the flow of electricity through a resistance network has enhanced our understanding of the system (Hillel, 1980). Soil water flow to plant roots has been studied by a great number of researchers. The microscopic approach (Gardner, 1960) considered the radial flow of water to a single root and the macroscopic or whole root system approach (Molz, 1971; Nimah and Hanks, 1973; Hillel et al., 1976) assumed the soil–root system to be a continuum in which water flow is essentially one-dimensional flow. One of the greatest difficulties is to estimate the resistances along the pathway. In general, the resistance to water flow in the rhizosphere and within the roots is calculated using empirical equations (Nimah and Hanks, 1973; Hillel et al., 1976).

Hearn and Constable (1984) presented a simple model to simulate the SPAC that calculates leaf water potential using empirical functions of crop age, evaporative demand

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$\theta_{ad}$</td>
<td>air dry soil water content (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\theta_i$</td>
<td>soil water content in layer $i$ (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\theta_{ll}$</td>
<td>lower limit of plant extractable water content (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\theta_{sat}$</td>
<td>saturated water content (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\theta_{ul}$</td>
<td>drained upper limit soil water content for soil layer $L$ (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>soil water content weighted to root distribution (cm$^3$ cm$^{-3}$)</td>
</tr>
<tr>
<td>$\rho_b$</td>
<td>soil bulk density (g cm$^{-3}$)</td>
</tr>
<tr>
<td>$\Psi_l$</td>
<td>leaf water potential (MPa)</td>
</tr>
<tr>
<td>$\Psi_s$</td>
<td>soil water potential (MPa)</td>
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and soil water deficit. Evaporative demand was calculated based on the model of Ritchie (1972) that separates soil evaporation and transpiration.

A water balance is usually necessary to simulate the root water uptake. Black et al. (1970) were able to describe the soil water balance with a semi-empirical representation of evaporation and drainage, without specifying the distribution of root water uptake. Nimah and Hanks (1973) suggested dividing the total root length in the profile in fractions in individual layers to distribute water uptake. A cascade approach is used in crop models such as CERES-Wheat (Ritchie et al., 1985) and CERES-Maize (Jones and Kiniry, 1986) to estimate the water distribution within the soil profile. The soil water movement and water uptake are functions of soil water content and root length density.

Despite the complexities of simulating root growth and the SPAC, several simplifications may be adequate in water balance and crop models, either for irrigation scheduling or for other management objectives which are linked to plant water status (e.g. application of plant growth regulators, pest and disease control, etc.). The aims of this work were: (1) to develop and test a simple, functional model to simulate cotton root growth, in response to thermal time, unfavorable conditions of soil resistance and soil water stress, and able to account for the spatial variation of soil properties, and (2) to develop and test a simple model of the SPAC for cotton crops, to simulate leaf water potential.

2. Materials and methods

2.1. Experiments

The experiments used to calibrate and validate the models (Table 1), were carried out in 1995–1997 at the Experimental Farm of the Instituto de Agricultura Sostenible in Córdoba, Spain (latitude 38°N, longitude 5°W, altitude 110 m). The time course of relevant climatic variables is represented in Fig. 1 for the three experimental periods. The soil was a Typic xerofluvent (USDA, 1975), Eutric Fluvisol according to the FAO system (FitzPatrick, 1980), with loam texture, without apparent restrictions for root growth to 3-m depth.

2.1.1. 1995 experiment

The cotton crop was planted on 11 April in rows 0.75 m apart to give a plant population after thinning of 5 plants m⁻². Each elemental plot consisted of eight 12-m long rows. There were three replications per treatment. The field was irrigated and fertilized (67 kg ha⁻¹ of N, P and K) before planting. The experimental design was a split-plot

| Table 1 | Experiments used for calibration and validation of each submodel |
|------------------------------------------|-------------------|-------------------|-------------------|
| Model/submodel | Parameters | Calibration | Validation |
| Soil resistance | Soil resistance | 1996 experiment | 1997 experiment |
| Root growth | Root growth | 1996 experiment | 1997 experiment |
| Leaf water potential | rₑ, rₑₑ, ψₛ | 1995 experiment | 1996–1997 experiments |
Fig. 1. Daily rainfall, solar radiation and average temperature during the 1995–1997 experiments periods. Cordoba, Spain.
with the irrigation treatment as the main factor and cultivar (Coker 310 and IRMA-1246) as the secondary factor. Only data for Coker 310 will be presented.

The irrigation treatments were early water stress (T1), mid-season stress (T2), late stress (T3) and a well-irrigated control (T4). The stress criterion was to maintain leaf water potential below \(-2.0\) MPa during two consecutive days. Irrigation was by sprinkler with amounts measured using rain gauges (two per elemental plot). The irrigation interval was about 11 days and the average water applications per irrigation were 68, 67, 68 and 73 mm for T1–T4, respectively. Nine irrigations were applied for T1, T2 and T4 and 8 for T3 (plus a pre-irrigation). The seasonal applied water was thus 611, 600, 544 and 660 mm for T1–T4, respectively. Rainfall during the cropping season was 23 mm.

The measured variables were leaf water potential \((\Psi_l)\), soil water content \((\theta)\) and leaf area index (LAI). \(\Psi_l\) was determined at pre-dawn and midday twice weekly on six leaves per treatment, using a pressure chamber (Soil Moisture Equipment Corp., Santa Barbara, CA, USA). The \(\theta\) was measured on the same days at various depths down to 3.0 m using a neutron probe (Campbell Nuclear Pacific, Pacheco, CA, USA) and a TDR system (model Trase 6050X1, Soilmoisture Equipment Corp., Santa Barbara CA) for the upper most layer. LAI was measured using a plant canopy analyzer (PCA) (model LAI 2100 LICOR Inc., Lincoln, NE, USA). Despite systematic pest treatments, some insect and disease damages were observed.

2.1.2. 1996 experiment

Two treatments, compacted (C, bulk density 1.62 Mg m\(^{-3}\) in the 0.20–0.40 m layer) and non-compacted sub-soil (NC, bulk density 1.46 Mg m\(^{-3}\)) were compared in a completely randomized experimental design with three replications per treatment. The procedure for compacting the 0.2–0.4 m layer may be found in Coelho et al. (2000). The elemental plots were 6 m \(\times\) 6 m in size. The cotton crop (cultivar Coker 310) was planted on May 13 and was sprinkler irrigated with an average water depth of 72 mm per irrigation at 12-day intervals. Six irrigations (plus a pre-irrigation) were applied. The seasonal applied water was 432 mm and rainfall during the cropping season was 268 mm. The measured variables were midday \(\Psi_l\), LAI, root length density \((L_r)\), \(\theta\) and soil penetrometer resistance (PR). Details of measurement techniques can be found in Coelho et al. (2000).

2.1.3. 1997 experiment

The 1996 experiment was repeated after removing the crop residue and tilling the top soil to 0.15-m with a rototiller. The experiment was planted on 5 May 1997 and received seven sprinkler irrigations of 64 mm average. The seasonal applied water was 448 mm and the rainfall during the cropping season was 192 mm. The measured variables were the same as in 1996 (for more details see Coelho et al., 2000).

2.2. Models

2.2.1. Root-growth model

The daily amount of dry matter partitioned to roots \((\Delta BM_{\text{root}}, \text{g m}^{-2} \text{ per day})\) is calculated from a simplified equation obtained using a more complex model of cotton
A unique relationship between $\Delta BM_{\text{root}}$ and shoot growth rate ($\Delta BM_{\text{shoot}}$, g m$^{-2}$ per day) was obtained for both rainfed and irrigated conditions at Córdoba running GOSSYM, finding:

$$\begin{align*}
\Delta BM_{\text{root}} &= 0.40 \Delta BM_{\text{shoot}}, & \text{if LAI} \leq 0.84 \\
\Delta BM_{\text{root}} &= 0.14 \Delta BM_{\text{shoot}}, & \text{if } 0.84 < \text{LAI} \leq \text{LAI}_{\text{max}} \\
\Delta BM_{\text{root}} &= 0, & \text{after LAI}_{\text{max}} \text{ is reached}
\end{align*}$$

(1)

where $\text{LAI}_{\text{max}}$ is maximum leaf area index. The above equation implies that the dry matter partitioning coefficient to roots is around 0.3 up to $\text{LAI} = 0.84$ and around 0.1 thereafter. If this submodel of root biomass is inadequate as part of a whole crop growth model, an alternative may be proposed in which root biomass is calculated as a continuous function of LAI:

$$\Delta BM_{\text{root}} = 5\text{LAI} \text{ for LAI} \leq 0.5 \text{ and } \Delta BM_{\text{root}} = 2.5 + 23.9(\text{LAI} - 0.5) \text{ for LAI} > 0.5, \text{ where } \Delta BM_{\text{root}} \text{ has units of g m}^{-2} \text{ per day}. \text{ LAI may be measured or calculated as a function of thermal time as suggested by Ritchie and Johnson (1990).}$$

The model transforms $\Delta BM_{\text{root}}$ to root length increment using:

$$\Delta RL = \Delta BM_{\text{root}} v$$

(2)

where $\Delta RL$ is root length increment (cm m$^{-2}$ per day) that will be distributed in the layers and $v$ (cm g$^{-1}$) is the ratio of length and mass of roots. As this parameter is not known, it was assumed equal to 17,000 cm g$^{-1}$ adopted by Villalobos et al. (1996) for sunflower.

Potential daily root depth increase ($\Delta RD$, cm per day) is calculated as a linear function of thermal time ($\text{TT}$, °C per day) above a base temperature of 12 °C if $\Delta BM_{\text{root}} > 0$:

$$\Delta RD = 0.3\text{TT}$$

(3)

The parameter 0.3 is the root depth increment per unit thermal time (cm °C$^{-1}$) as measured in the 1996 field experiment (Coelho et al., 2000).

The potential root depth increase is corrected by soil water deficit and soil resistance to penetration represented by two factors, $f_a$ and $f_r$ (range 0–1), respectively. The $f_a$ value is 1 for soil available water greater than 25% then decreasing linearly to 0 for zero available water.

According to Taylor and Gardner (1963) cotton roots stop growing at a penetration resistance $PR = 3.0$ MPa. Therefore, in the model $f_r = 0$ for PR equal to or greater than 3 MPa. For PR less than 1 MPa, more than 70% of cotton roots are able to grow, thus we have fixed $f_r = 1$ for that interval. Finally, in the 1–3 MPa range we have assumed a linear reduction in root growth.

The model accounts for the variation of PR as a function of soil water content ($\theta$, cm$^3$ cm$^{-3}$) and soil bulk density ($\rho_b$, g cm$^{-3}$) (Taylor and Gardner, 1963; Ehlers et al., 1983) using the following equation calibrated in the 1996 experiment:

$$PR = -6.58 + 8.96\rho_b - 30.4\theta,$$

$$n = 39, \ r^2 = 0.86, \ \text{RMSE} = 0.43 \text{MPa}$$

(4)

The potential root depth increase is then corrected by a stress factor ($f_s$) which is the minimum of $f_a$ and $f_r$. 

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The distribution of root growth among the layers follows the approach of CERES-type models (e.g. Villalobos et al., 1996). An intermediate variable $F_i$ is calculated for each $i$ layer:

$$F_i = \frac{RD_i}{RD} f_s e^{-d_i/100}$$

where $RD$ is the total root depth (cm) in the profile, $RD_i$ (cm) the root depth in the $i$ layer (equal to the layer thickness if the root has crossed the layer) and $d_i$ is the depth (cm) down to the center of the $i$ layer. The exponential function in Eq. (5) is an extinction coefficient indicating that the priority for root growth reduces from 1 to 1/3 from the topsoil to 1-m depth. Then the model calculates the root distribution factor (RDF$_i$), the root length increment ($\Delta RL_i$, cm m$^{-2}$ per day) and the root density increment ($\Delta LN_i$, cm cm$^{-3}$) for each $i$ layer using the following equations:

$$\text{RDF}_i = \frac{F_i}{\sum_{j=1}^{m} F_j}$$  \hspace{1cm} (6)

$$\Delta RL_i = \text{RDF}_i \Delta RL$$  \hspace{1cm} (7)

$$\Delta LN_i = \frac{\Delta RL_i}{z_i}$$  \hspace{1cm} (8)

where $z_i$ (cm) is the thickness of layer $i$ and $n$ the number of layers. The root density of the $i$ layer ($LN_i$, cm cm$^{-3}$) is the accumulated $\Delta LN_i$ values with time.

The model assumes that soil bulk density of each layer follows a normal distribution. The root growth in the layer is represented by the mean of 100 plants growing simultaneously. When root growth starts in one layer, a random $\rho_b$ is generated by the model for each plant according to the Box–Müller method (Morgan, 1988). Depending on the $\rho_b$ generated, and thus, on estimated soil resistance (Eq. (4)), the root will grow vertically (if PR is low) or will grow horizontally “searching” for areas of lower resistance, in which case the depth growth will be zero. After simulating the daily growth of 100 plants the model calculates the mean growth and sums this value to root depth of the average plant representative of the crop. The following day, the model generates new $\rho_b$ values for the plants with roots that did not grow vertically the day before. This assumes that in their horizontal growth the roots go to points of different $\rho_b$. This procedure continues until all plants have found a point where they can grow vertically or until the main root of the representative plant has reached the bottom of the layer. The coefficient of variation of bulk density was assumed to be 0.07 in the upper 0.15-m layer, 0.03 below 0.3 m and 0.03 and 0.07 for the 0.15–0.30 m layer, for NC and C, respectively, as were found in the field experiments.

2.2.2. Soil water balance model

The water balance includes rain and irrigation, soil evaporation, transpiration, run-off and drainage. Surface run-off is predicted from daily precipitation using an adaptation (Williams, 1991) of the SCS curve number method (Soil Conservation Service, 1972).

For soil water content, several parameters are required for each soil layer (Ritchie, 1981): the saturated water content ($\theta_{sat}$), the air–dry water content ($\theta_{ad}$), the drained upper
limit ($\theta_{ul}$), and the lower limit of plant extractable water ($\theta_{ll}$). Infiltrated water (precipitation minus run-off) is redistributed following a cascade approach. First, water above $\theta_{ul}$ is moved from layer to layer (or out of the soil profile) instantly. Second, the amount of drainage out of a given layer is proportional to soil water content above $\theta_{ul}$ and a drainage soil parameter which is 0.6 for the experimental soil.

Maximum crop evapotranspiration is calculated (Appendix A) as a function of the equilibrium evaporation rate defined by Priestley and Taylor (1972), the maximum temperature according to Jones and Ritchie (1990) and a correction factor locally calibrated (Mantovani, 1993). The computation of soil and plant evaporation is based on Ritchie’s (1972) model adapted after some modifications to water balance in layered soils (Jones et al., 1986). Soil evaporation is subtracted from the water content of the upper soil layer to a minimum value of $\theta_{ad}$.

Upward flow of water to replace evaporated moisture is calculated according to Jones et al. (1986). The potential plant evaporation is calculated as a function of LAI. Actual water extraction from each layer is calculated accounting by the relative root length and by the relative water availability in each layer (Appendix A).

2.2.3. Leaf water potential model

The leaf water potential model (LWPM) is based on an Ohm’s Law analogue, where the water flux from soil to the atmosphere through the plant ($T$, mm per day) is a function of the difference in water potential between the evaporating leaves ($\Psi_1$, MPa) and the soil surrounding the roots ($\Psi_s$, MPa), and the resistance to flow which is the sum of the resistance in the soil surrounding the roots ($r_s$, MPa mm$^{-1}$ per day), within the roots ($r_r$, MPa mm$^{-1}$ per day) and in the xylem ($r_x$, MPa mm$^{-1}$ per day). $\Psi_1$ is thus calculated by

$$\Psi_1 = \Psi_s - (r_s + r_r + r_x)T$$

(9)

Under conditions of non-limiting water supply $\Psi_s$ and $r_s$ are negligible. The total resistance is then given by the plant flux resistance $r_{ns}$ (MPa mm$^{-1}$ per day):

$$r_{ns} = r_r + r_x$$

(10)

and $T$ reaches its maximum value ($T_{max}$). Therefore,

$$r_{ns} = -\frac{\Psi_1}{T_{max}}$$

(11)

Under conditions of water stress the plant flux resistance ($r_{es}$, MPa mm$^{-1}$ per day) is

$$r_{es} = r_s + r_{ns}$$

(12)

with $r_s$ calculated as

$$r_s = \frac{\Psi_s - \Psi_1}{T} - r_{ns}$$

(13)

The resistance $r_{ns}$ is calculated as $-(-0.9)/T_{max}$, where $-0.9$ is the maximum midday leaf water potential value (MPa) observed in the 1995 experiment. The transpiration is calculated in the soil water balance submodel (Appendix A). $\Psi_s$ is calculated assuming it equals the predawn leaf water potential obtained from an empirical function of the soil
water content weighted by root distribution ($\theta_w$, cm$^3$ cm$^{-3}$) fitted to data collected in 1995:

$$\Psi_s = -45.1 e^{-36.9\theta_w}, \quad n = 144, \quad r^2 = 0.65, \quad \text{RMSE} = 0.34 \text{MPa}$$  \hspace{1cm} (14)

The resistance $r_s$ is calculated using another empirical function fitted to data from Eq. (13) and relative soil water deficit weighted to root distribution (SWD$_w$, fraction):

$$r_s = \begin{cases} 
0.621 e^{0.917 \text{SWD}_w}, & \text{if SWD}_w < 0.6 \\
13.061 \text{SWD}_w^2 - 12.401 \text{SWD}_w + 3.833, & \text{if SWD}_w \geq 0.6
\end{cases}$$

(15)

The data used for fitting Eq. (15) were also obtained from the 1995 experiment, using $n = 61$ data points and yielding a $r^2$ of 0.81 and a RMSE of 0.19 MPa mm$^{-1}$ per day.

3. Results

3.1. Root-growth model

The data set of 1997 was used to validate the submodel of soil penetration resistance and the submodel of root growth (Table 1). The RMSE (root mean square error, Willmot, 1982) for predicting the resistance to penetration was 0.49 MPa. The slope (0.84) and the intercept (0.28 MPa) of the linear regression ($r^2 = 0.82$) fitted to the data were not significantly different ($P = 0.01$) from 0 and 1, respectively (Fig. 2). The agreement is good despite using values of soil water content simulated by the soil water balance model.

Table 2 shows the linear regression equations of simulated $L_n$ on measured $L_n$ for each soil layer. The model provided good estimates of root length density for all depths with RMSE below 0.5 cm cm$^{-3}$. The agreement was poor at 135 and 225 cm, but note that measured values showed a large variability. The intercepts of the linear regressions were
significantly different \((P = 0.05)\) from 0 and the slopes were not significantly different \((P = 0.05)\) from 1, and explained more than 60\% of the observed variability in the profile. The performance of the model can be considered satisfactory when compared with the variations observed in more complex models such as those of Grant (1993), Asseng et al. (1997) and Jourdan and Rey (1997).

The results of root-growth simulation for the NC and C treatments of the 1997 experiment are presented in Fig. 3. At the beginning, the model underestimates \(L_n\) for both treatments and reaches a maximum difference of around 0.8 cm cm\(^{-3}\), 67 days after emergence. The values simulated 102 days after emergence are very close to those measured, except in the 0.15–0.30 m layer. In the compacted layer the model always underestimated \(L_n\) but the difference between measured and simulated data never exceeded 0.5 cm cm\(^{-3}\).

The initial underestimate of the model may be associated with an incorrect estimate of dry matter partitioning to roots or to the effect of the limiting factors, which are also dependent on other model predictions. In any case, the model clearly captures the main features of root growth as affected by soil compaction.

### 3.2. Soil water balance model

The two data sets used to validate the soil water balance model are those of 1995 and 1997. ET was calculated for periods without rain or irrigation as total soil water depletion down to 2.70-m depth, which assumes nil drainage below this depth. Simulated ET did not differ from measured ET (Fig. 4). The slope and intercept of the linear regression were not significantly \((P = 0.05)\) different from 1 and 0, respectively, and explained more than 83\% of the observed variability. The simulation of crop ET was good for treatments under water stress (1995 experiment) and treatments with alterations in soil structure (1997 experiment).
The simulation of total soil water down to 2.70 m was good for all experiments, with few exceptions (Fig. 5). The intercept of the linear regression fitted to the simulated/observed relationship was significantly different ($P = 0.05$) from 0 and the slope was not significantly different ($P = 0.05$) from 1. The regression explained more than 87% of the observed variability.

Fig. 3. Measured vs. simulated cotton root length density in the soil profile on various days after emergence (DAE) in the 1997 experiment: (a) non-compacted (NC) treatment, (b) compacted (C) treatment.

The simulation of total soil water down to 2.70 m was good for all experiments, with few exceptions (Fig. 5). The intercept of the linear regression fitted to the simulated/observed relationship was significantly different ($P = 0.05$) from 0 and the slope was not significantly different ($P = 0.05$) from 1. The regression explained more than 87% of the observed variability.
Predictions of soil water content were satisfactory for all depths, despite the simplicity of the submodels of soil water flow and root water extraction. The RMSE varied between 0.0033 cm$^3$ cm$^{-3}$ (240–270 cm depth) and 0.0316 cm$^3$ cm$^{-3}$ (15–30 cm depth) depending on depth. The slopes of the linear regressions fitted to the simulated/observed data for each depth were not significantly different ($P = 0.05$) from one, and the intercepts for all depths were not significantly different ($P = 0.05$) from 0, except for the 0.30–0.60 and 1.50–1.80 m layers. The model explained more than 70% of the observed variability in the soil profile.


Fig. 5. Measured vs. simulated total soil water down to 2.70-m, 1995 and 1997 experiments. Explanation to the legend as in Fig. 4.
Fig. 6. Time course (in days after emergence, DAE) of measured and simulated soil water content at several depths in the 1997 experiment: (a) non-compacted (NC) treatment, (b) compacted (C) treatment. Cordoba, Spain.
Fig. 6 shows the seasonal variation of measured and simulated soil water content for the 1997 experiment. One of the simplifications of the model is the use of a single drainage factor for the whole profile. In the compacted treatment of the 1997 experiment, it is evident that soil water content above the compacted layer (0.15–0.30 m) is underestimated while soil water content below (0.30–0.60 m) is overestimated. This arises because the model does not take account of the reduced hydraulic conductivity of the compacted layer.

### 3.3. Leaf water potential model

Validation of the model was performed using data from the 1996 and 1997 experiments that had not been used for model calibration (Table 1). The slope and intercept of the linear regression of simulated on measured midday Ψ₁ were not significantly (P = 0.05) different from 1 and 0, respectively, and explained more than 71% of the observed variability. Fig. 7 shows a comparison of our model and the model of Hearn and Constable (1984). The RMSE of the estimations using Hearn and Constable’s model was 0.34 MPa while with our model it was 0.22 MPa. However, discrepancies still persist for very low midday Ψ₁, indicating that other factors not considered by our model (e.g. changes in resistance to water transport) may come into play when water stress is severe. One example of the seasonal variation of midday Ψ₁ is shown for the NC treatment in 1996 (Fig. 8). The model approximately predicted the time course of midday Ψ₁. The variation observed in the Ψ₁ simulation in the C treatment is probably related to the variability of the penetration resistance in the compacted layer.

### 3.4. Sensitivity analysis

The sensitivity of seasonal ET and leaf water potential to changes in the different parameters of the model (root depth increase per growing degree per day, ratio of root length to root mass, soil resistance for zero root growth and leaf water potential of non-stressed crops)
was assessed by changing the standard value in $\pm 20\%$ for the 1995 experiment. It was observed that the sensitivity coefficients were always higher for compacted conditions, and that the sensitivity was low for all the parameters in the NC treatment and for both the ratio of root length to root mass and the leaf water potential of non-stressed crops for the C treatment. However, the sensitivity was very large (greater than 1) for reductions in the root depth increase per unit thermal time or in the resistance limit for root growth in the compacted treatment.

4. Discussion

The models presented in this paper were constructed in order to simplify existing soil water modules used in cotton models (e.g. GOSSYM) and to include estimates of leaf water potential because it is widely used as a predictor of crop performance (expansion growth, leaf conductance, effects of pests, water status). The addition of compaction effects was intended to assess cotton performance in tropical areas of Africa where there are extensive problems of soil compaction.

The proposed soil water balance module provided good estimates of evapotranspiration but predictions of soil water content by layer were poor in several cases. The model uses the water cascade approach with a parameter for calculating drainage (the fraction of soil water above field capacity which is lost per day) that is constant for the whole soil profile. This assumption is clearly inappropriate when a compacted layer exists and explains, partially at least, the inadequate predictions of soil water distribution. Using specific drainage parameters for each layer should improve model performance but calibration would be more complex. Further research should explore simple methods to adjust the calibration parameter for variation in soil bulk density.

Simulation of compaction effects focussed on root growth as affected by penetration resistance. This was based on empirical relations of resistance as a function of bulk density.

Fig. 8. Time (days after emergence, DAE) course of midday leaf water potential for non-compacted (NC) treatment of 1996 experiment.
and soil water content (Coelho et al., 2000). Good performance of the penetration resistance model was expected as calibration and validation were performed on the same soil. Applying the model to different soils would require calibration of the resistance function although our function would probably apply to similar soils (medium texture, massive structure, low organic matter content). Future studies in other soils may provide sufficient information to obtain more general relationships for calculating penetration resistance.

The predictions of root length density were good in qualitative terms but large errors were observed in many cases. Root growth was predicted as a function of resistance, depth and soil water content. It is clear that several complex feedbacks operate in the root-growth–water balance model: for instance, root length density affects water uptake and thus changes in soil water content, which in turn, affects penetration resistance. These feedbacks may be responsible for some of the incorrect predictions and deserve further study.

The main effects of the compacted soil layer on root growth were a delay in root penetration increase rate and a reduction in total root length, which were captured by the model. The model takes into account spatial variability of soil resistance to predict root depth increase, based on previously measured bulk density variability in this soil. A simple simulation experiment was performed using the model with different distributions of bulk density (average and standard deviations). In general, it was observed that with high average bulk density a larger variability improves the penetration of roots but at small root densities. If variability is small, roots concentrate in the topsoil above the compacted layer. The effects of variability on root growth are also subject to feedback effects. Soil areas with low bulk density have higher hydraulic conductivity, thus providing preferential pathways for water and nutrients flow and locations for root growth to concentrate. However, in the long term, high root densities increase water uptake and reduce soil water content. In any case, the overall effect of variability will depend on irrigation management (frequency and amounts). For instance keeping the soil close to field capacity by preplant irrigation will maintain a low soil resistance during early stages of crop growth. Root growth will concentrate in areas of low bulk density. If irrigation is delayed the conditions in those areas will soon become limiting for root growth, emphasizing how the interaction between irrigation and soil conditions will determine the actual performance of the root system.

Predictions of leaf water potential using our model are only slightly better than those from the model of Hearn and Constable (1984). The main advantage of our model however is its attempt to provide a mechanistic basis for the simulation. More detailed research will be required to propose general relationships between crop state variables (e.g. leaf area, root length density, etc.) and the resistance to flow through soil and plant. Alternatively short time-step models (e.g. Connor and Fereres, 1999) may be required to improve the prediction of midday leaf water potential.

5. Conclusions

The simple root-growth model simulated correctly the temporal and spatial distribution of roots in the profile, thus offering a valid alternative to more complex models. The water
balance model performed well for simulating total soil water, even when a compacted layer was present; however the results for water content per layer need improvement, particularly in zones of great root concentration. Midday leaf water potential was adequately predicted, though model validation was restricted to values above \(-2.2\) MPa, probably sufficient for irrigated cotton crops but not for rainfed conditions. Soil water flow and root water uptake models as those presented in this paper are required for irrigation management. Their relative simplicity will help in spreading their adoption.

Acknowledgements

The European Union, DG XII, Contract TS3.CT.94.0288, funded this research. M.B. Coelho was supported by CAPES/MEC, Brazil, while doing this research in Spain.

Appendix A. Calculation of transpiration and root water uptake

A.1. Crop transpiration

Crop maximum evapotranspiration (\(ET_{\text{max}}\), mm per day) is calculated as proposed by Jones and Ritchie (1990) and corrected according to Mantovani (1993):

\[
ET_{\text{max}} = F \times ET'_{\text{max}}
\]

where

\[
\begin{align*}
ET'_{\text{max}} &= 1.1\text{EEQ}, & \text{if } 5 < t_{\text{max}} < 35 \\
ET'_{\text{max}} &= [1.1 + 0.05(t_{\text{max}} - 35)]\text{EEQ}, & \text{if } t_{\text{max}} > 35 \\
ET'_{\text{max}} &= 0.01 e^{(0.187t_{\text{max}}+20)\text{EEQ}}, & \text{if } t_{\text{max}} < 35
\end{align*}
\]

where EEQ (mm per day) is the equilibrium evaporation and \(t_{\text{max}}\) the maximum temperature in °C (Jones and Ritchie, 1990).

The correction factor \(F\) is calculated as (Mantovani, 1993)

\[
F = \begin{cases} 
1 + 0.074\text{LAI}, & \text{if } \text{LAI} \leq 2.7 \\
1.2, & \text{if } \text{LAI} > 2.7
\end{cases}
\]

When soil water is non-limiting, crop transpiration (\(T_{\text{max}}\), mm per day) is calculated as

\[
\begin{align*}
T_{\text{max}} &= ET_{\text{max}}(1 - e^{-\text{LAI}}), & \text{if } \text{LAI} \leq 3 \\
T_{\text{max}} &= ET_{\text{max}}, & \text{if } \text{LAI} > 3
\end{align*}
\]

A.2. Root water uptake

For each layer root water uptake is calculated as

\[
RWU_i = \frac{T_{\text{max}} \text{SWD}_i \text{FR}_i \text{FW}_i}{S_{\text{FR}} \times \text{FW}}
\]
where SWD$_{f1}$ is a 0–1 factor accounting for the effect of soil water on transpiration:

$$\begin{align*}
\text{SWD}_f &= 1, & \text{if } \text{SWD}_w \leq 0.5 \\
\text{SWD}_f &= 2.5(1 - \text{SWD}_w), & \text{if } \text{SWD}_w > 0.5
\end{align*}$$

(A.6)

where SWD$_w$ is the soil water deficit weighted according to root length distribution:

$$\text{SWD}_w = \sum_{i=1}^{m} \frac{\theta_{ub_i} - \theta_i}{\theta_{ul_i} - \theta_{ll_i}} \text{FR}_i$$

(A.7)

where FR$_i$ is the fraction of total root length located in the $i$th layer; FW$_i$ the fraction of total soil water present in layer $i$ and

$$S_{FR \times FW} = \sum_{i=1}^{m} \text{FR}_i \text{FW}_i$$

(A.8)

Finally, crop transpiration ($T$, mm per day) is calculated as

$$T = \sum_{i=1}^{m} \text{RWU}_i$$

(A.9)

References


