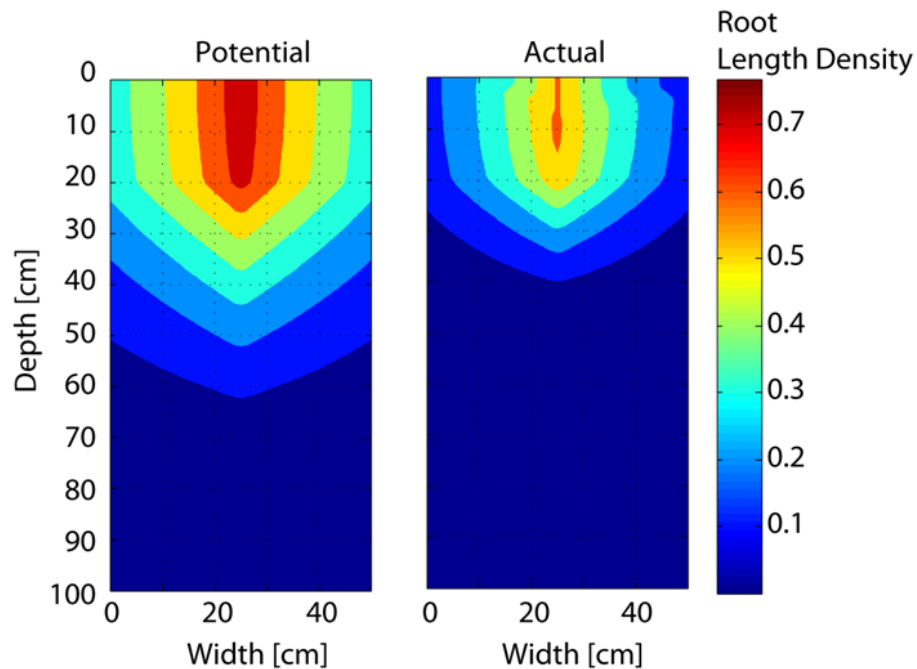


HYDRUS

ROOT GROWTH MODULE

VERSION 1.02



Technical Manual

by

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Abstract

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This report documents version 1 of the HYDRUS root growth module. The Root Growth module was developed as a supplemental module of the HYDRUS software package (both Hydrus-1D and HYDRUS (2D/3D)), to model the root growth as a function of different environmental stresses. The root growth model is based on the approach developed by Jones et al. (1991). The model assumes that various environmental factors can influence the root development under suboptimal conditions. These environmental factors are characterized by various growth stress factors. Root growth and the development of root length density then depend on environmental factors when the stress factor approach is used. This text provides a detailed description of the implemented model, as well as several test examples demonstrating various features of this model.

DISCLAIMER

This report documents version 1 of the HYDRUS root growth module. The Root Growth module was developed as a supplemental module of the HYDRUS software package (both Hydrus-1D and HYDRUS (2D/3D), to model the root growth as a function of different environmental stresses. The software has been verified against selected test cases. However, no warranty is given that the program is completely error-free. If you do encounter problems with the code, find errors, or have suggestions for improvement, please contact one of the authors at

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Implementation of Interactions Between Plant Roots, Soil Properties, and Water Flow Conditions in Soil into HYDRUS-1D

1. General Information

The standard version of HYDRUS-1D (Šimůnek et al., 2008) does not consider the feedback between the root growth and conditions in the soil and the root growth is fully defined using input parameters (Šimůnek and Hopmans, 2009). In the modified version of HYDRUS-1D described in this text, the root growth and the roots spatial distribution is dynamically affected by various environmental factors such as soil water content or soil temperature.

Input parameters describing interactions between plant roots, soil properties, and water flow conditions in soils required by a modified HYDRUS-1D code are provided using a new input file Root.in. To use these new options in connection with the GUI of HYDRUS-1D, in the “Root Growth Parameter” window select that the root depth should be specified “With Time-Variable Boundary Conditions”.

The implemented approach is based on the root growth model of Jones et al. (1991). The model assumes that various environmental factors influence the root development under suboptimal conditions, which are characterized by various growth stress factors. Root growth and the development of root length density then depend on environmental factors when the stress factor approach is used.

The calculation of the actual root length density distribution is based on the use of the potential (root distribution) shape functions. Such functions represent the potential root length density distribution under optimal development conditions when no restrictions on the root growth occur. Due to sub-optimal environmental conditions, a potential root distribution can be altered to an actual root distribution. Figure 1 shows a possible transformation of the potential root length density distribution to an actual distribution.

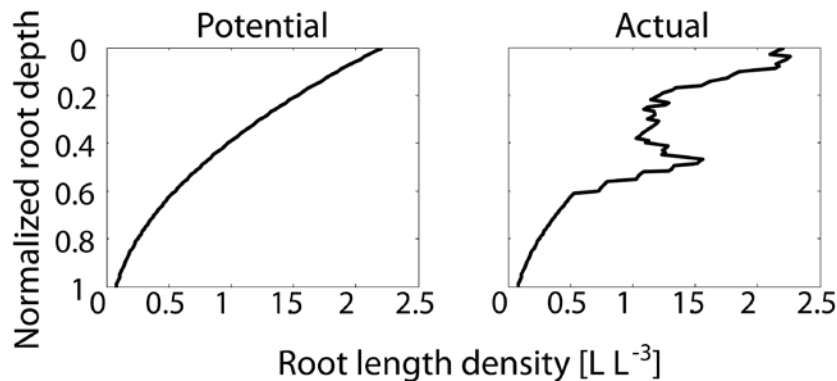


Figure 1. Schematic illustration of the potential root length density distribution (left) being modified due to various stress factors to the actual root length density distribution (right).

2. Description of the Rooting Pattern using the Root Length Density Functions

For describing the potential root length density distribution the user can choose between five different root length density distribution functions (Hao, 2005; Jones et al., 1991; and Vrugt et al., 2001). Table 1 lists the implemented models (equations) of relative root length density distribution functions and Figure 2 shows their graphical representations. The root length density distribution model proposed by Vrugt et al. (2001) is the most flexible model. Users need to specify the parameters p_z and z^* in the Root.in file, which are there referred to as PZ and Zv , respectively. Functions shown in Figure 2 (4a and 4b) were obtained by different parameter settings in the root length density distribution model of Vrugt et al. (2001).

Table 1. Root length density distribution models implemented in HYDRUS-1D (zr is the normalized root depth).

Model	$b(z_r)$	Reference
1	$2.938-2.462z_r$	modified after Zuo et al. (2004)
2	$4.522(1-z_r)^{5.228} \cdot e^{(9.644z_r)^{2.426}}$	
3	$2.21-3.72z_r+3.46 \cdot (z_r)^2-1.87(z_r)^2$	Wu et al. (1999)
4	$[1-z_r]e^{-\frac{P_z}{z_m} z^*-z_r }$	Vrugt et al. (2001)
5	$(1-\frac{z_r}{3})^3$	Jones et al. (1991)

Root length density distributions calculated by these models represent the potential root length density distribution pattern which would be obtained under optimal conditions when no restrictions of root growth, such as hydrotropism and root senescence were considered. All models are expressed using a normalized root depth, which is scaled to get the actual rooting depth.

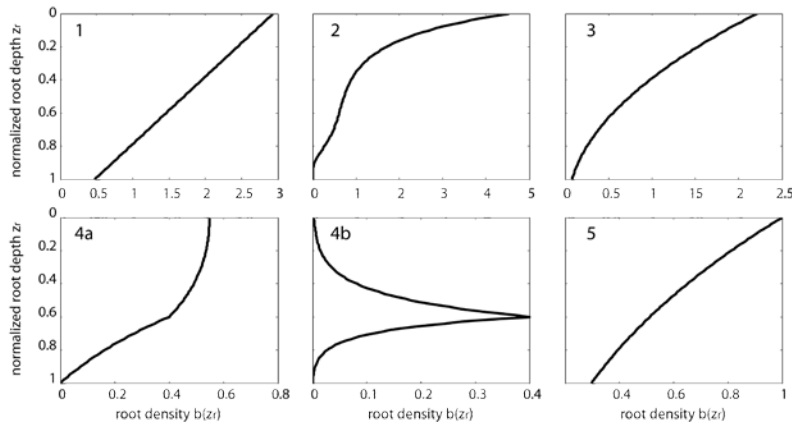


Figure 2. Graphical representation of implemented root length density models.

3. Root Growth Simulation

Users can choose between three different approaches to describe the potential root growth. In addition to the approach currently available in HYDRUS-1D (using the time-dependent logistic growth function; the first approach), the root growth can be simulated either as a time-dependent process (the second approach) or as a thermal time dependent process (the third approach) using the sinusoidal growth function. When the root growth is considered to be dependent either on time or thermal time, the *RGR* parameter in the Root.in file should be set to 1 or 2, respectively.

In both the first and second approach, root growth depends on time. When the second approach is used, the following equation is used to calculate the potential increase (dd_i) of the rooting depth (Hao, 2005):

$$dd_i = \left[R_D \left(0.5 + 0.5 \cdot \sin \left(3.03 \cdot \frac{t_P}{t_M} - 1.47 \right) \right) \right] - Z_j \quad (1)$$

When this equation is used, the maximum rooting depth (R_D), and the time to maturity (t_M) have to be provided. Z_j represents the potential rooting depth at the previous time step.

When the second approach is used, users can specify whether planting takes place during the simulated period, has already occurred at a specific time before the start of the simulation, or occurs at the beginning of the simulation. Users have to specify the time after planting (t_P) and how much time to maturity of the crop (t_M) is left at the start of the simulation. If planting takes place after the start of the simulation, the parameter t_P should be set equal to 0 and the additional parameter Δt_P (time to planting) has to be set to the time when planting takes place after the start of the simulation. The t_M parameter then has to be set to the remaining time to the crop maturity at the time of planting. If planting takes place at the beginning of the simulation or has already took place before that, the Δt_P parameter has to be set equal to 0 and the initial rooting depth has to be specified using the D_p parameter (the planting depth). The units of the parameters referring to a time have to be equal to units used in HYDRUS.

When the root growth is considered to be dependent on thermal time, the *RGR* parameter has to be set to 2. The following equation is used to calculate the potential increase in root growth (Ireson, 2009):

$$dd_i = TG \cdot D_{tt} \quad (2)$$

where TG is an empirical factor, which can be changed by the user, and D_{tt} [$^{\circ}\text{C}\cdot\text{day}$] represents a single day thermal time, which is calculated using the following equation:

$$D_{tt} = \min[T_{\max} - T_{\min}; \max(0; T_c - T_{\min})] \quad (3)$$

where T_{can} represents the mean daily canopy temperature, which has to be provided by users as an additional boundary condition. These values are specified in an additional input file Temp.In. Users have to provide the mean temperature for each day of the calculation.

T_{max} and T_{min} represent the maximum and minimum temperatures for the development of a particular crop. These parameter values have to be provided by users, together with the upper limit of the cumulated thermal time (TT_{max}) when root growth stops.

The actual increase (d_r) of the rooting depth is calculated by reducing the potential increase in the rooting depth due to stress factors (SF):

$$d_r = dd_i \cdot \min(SF) \quad (4)$$

Stress factors influencing the vertical penetration of roots according to Jones et al. (1991) are listed in Table 2. The stress factors range from 0 (no growth) to 1 (no stress).

Table 2. Stress factors influencing root growth.

Parameter	Stress Factor
S_T	Temperature stress
S_{Ca}	Calcium deficiency
S_{Al}	Aluminum toxicity
S_{St}	Soil strength
S_{Ae}	Aeration stress
S_{CF}	Excessive coarse fragments

4. Environmental Factors Affecting Root Growth

The user can define whether a particular stress factor is considered during the simulation or not. According to Jones et al. (1991), stress factors can be divided into static and dynamic stress factors. Stress factors due to aluminum toxicity, calcium deficiency, and coarse fragments are considered to be static. Stress factors due to temperature stress and/or soil strength (which depends on water content) are considered to be dynamic.

4.1. Static Factors

When the **aluminum stress** is to be considered, the *AYN* parameter in the *Root.in* file has to be set to 1. To consider the stress factor due to **aluminum toxicity**, the threshold value of aluminum saturation at which root growth is first affected (Al_A) and the value at which it is completely inhibited (Al_X) have to be provided by the user. The user also has to specify the amount of KCl-extractable Al (Al_E) and the value of the sum of NH_4OAC -extracted bases (sum of bases, *SMB*).

According to Jones et al (1991), the aluminum saturation (Al_S) is calculated first using the cation exchange capacity (*CEC*):

$$CEC = SMB + Al_E$$

$$Al_s = \frac{Al_E}{CEC} \cdot 100 \quad (5)$$

The stress factor due to aluminum saturation is then calculated as:

$$S_{Al} = \frac{Al_X - Al_S}{Al_X - Al_A} \quad Al_A \geq Al_S \geq Al_X \quad (6)$$

When the **calcium stress** is to be considered, the *CYN* parameter in the *Root.in* file has to be set to 1. With regards to the stress due to **calcium deficiency**, the user has to define threshold values, at which root growth begins to be affected (Ca_A) and completely inhibited (Ca_X). The amount of exchangeable calcium (*Ca*) has to be provided as well. According to Jones et al. (1991), the stress factor is calculated using the calcium saturation (Ca_S):

$$Ca_s = \frac{Ca}{CEC + 10^{-20}} \cdot 100$$

$$S_{Ca} = \frac{Ca_s - Ca_x}{Ca_a - Ca_x} \quad Ca_a \geq Ca_s \geq Ca_x \quad (7)$$

Jones et al. (1991) states that **coarse fragments** reduce the volumetric water holding capacity and nutrient availability approximately in proportion to their volumetric fraction. To consider the

effect of coarse fragments on root growth, the user has to specify the volume fraction of particles bigger than 2 mm (*ROK*) for each material. The stress factor is then calculated as:

$$S_{CF} = 1.0 - ROK \quad (8)$$

The influence of coarse fragments can be neglected by setting the value of *FYN* to 0.

4.2. Dynamic Factors

According to Jones et al. (1991), the **soil strength stress** factor is determined using the bulk density, soil texture, and the water content. The bulk density above which root growth is negligible at the optimum soil water content (BD_X) and the bulk density below which root growth is negligible at the optimum soil water content (BD_O) is calculated first using the weight percent of sand (*Sand*) for each material:

$$\begin{aligned} BD_X &= 1.6 + 0.004 \cdot Sand \\ BD_O &= 1.1 + 0.005 \cdot Sand \end{aligned} \quad (9)$$

A factor for the interacting effects of texture and bulk density of the moist soil is then calculated as follows:

$$S_{BD} = \begin{cases} 1 & BD < BD_O \\ \frac{BD_X - BD}{BD_X - BD_O} & BD_O \geq BD \geq BD_X \\ 0 & BD > BD_X \end{cases} \quad (10)$$

The bulk density (*BD*) has to be thus provided by the user for each material. The effect of the bulk density can be neglected by setting the *BDYN* parameter to 0.

Soil water contents lower than the soil water content, for which S_{BD} was determined, will increase the soil strength and thereby reduce rooting. To consider the influence of the water content on soil strength and root growth, the parameter describing the fractional water content (θ_f) of each soil layer is calculated and used to evaluate the soil strength stress factor (S_S):

$$\begin{aligned} \theta_f &= 0 & \theta < \theta_L \\ \theta_f &= \frac{\theta - \theta_L}{\theta_U - \theta_L} & \theta_U \geq \theta \geq \theta_L \\ \theta_f &= 1 & \theta > \theta_U \\ S_S &= S_{BD} \cdot \sin(1.57 \cdot \theta_f) \end{aligned} \quad (11)$$

where θ is the water content at each time step, θ_L is a lower limit of the plant-extractable soil water for the fine soil fraction, and θ_U is a drained upper limit of the soil water for the fine soil fraction. In our implementation, instead of the water content, users have to define the soil tension, which is then used to calculate the corresponding water content using the soil hydraulic properties.

To consider the effect of **poor aeration** in highly saturated soils, the model calculates a critical water-filled porosity (θ_{eC}) (critical effective saturation) from the soil texture:

$$\begin{aligned}\theta_{eC} &= 0.4 + 0.004 \cdot \text{Clay} \\ \text{Clay} &= 100 - \text{Sand} - \text{Silt}\end{aligned}\quad (12)$$

where *Sand*, *Silt*, and *Clay* are weight percentages of the sand, silt, and clay soil fractions. The user has to provide information about the percentages by weight of sand (*Sand*) and silt (*Silt*).

To define a user-specified critical water filled porosity θ_{eC} , the parameter *CW* has to be set to 1 (otherwise the value has to be 0) and the defined value has to be assigned to the parameter *CWFP* in the input file. The **aeration stress** factor (S_{Ae}) is then calculated as:

$$\begin{aligned}S_{Ae} &= S_{FT} + (1 - \theta_e) \cdot \frac{1 - S_{FT}}{1 - \theta_{eC}} \\ S_{Ae} &= 1 \quad \theta_e < \theta_{eC}\end{aligned}\quad (13)$$

where θ_e is the water-filled porosity (effective saturation), which is defined as the ratio of the water content in each node at each time step and the saturated water content, θ_s , which is provided as a parameter of the soil hydraulic properties for each material. S_{FT} is a parameter defining the fraction of normal root growth when the pore space is saturated (0-1) and has to be set by the user. Setting S_{FT} equal to 1 means that flooding has no effect on root growth. Setting S_{FT} equal to 0 means that there is no root growth in saturated soils. The value of S_{FT} therefore depends on the crop type.

To consider the stress due to **soil temperature** the user can choose between two approaches. The first approach considers only the stress due to low temperature. The second approach also considers for stress due to high soil temperatures.

When the first approach of Jones et al. (1991) is used, the user has to specify a minimum temperature when the root growth starts (T_{\min}) and the optimum temperature for root growth (T_{Opt}). The **temperature stress** factor is then calculated as:

$$\begin{aligned}S_T &= 0 & T < T_{\min} \\ S_T &= \sin\left(1.57 \cdot \frac{T - T_{\min}}{T_{Opt} - T_{\min}}\right) & T \in (T_{\min}, T_{Opt}) \\ S_T &= 1 & T > T_{Opt}\end{aligned}\quad (14)$$

where T is the soil temperature calculated by HYDRUS-1D.

When using the second approach the user has to also specify a value of the maximum temperature for root growth (T_c) and the value of the shape coefficient ct . The **temperature stress** factor is then calculated using the following equation (Yin et al., 1995; Yin and van Laar, 2005):

$$S_T(t, T) = \left[\left(\frac{T_c - T(t)}{T_c - T_{opt}} \right) \cdot \left(\frac{T(t) - T_{min}}{T_{opt} - T_{min}} \right)^{\frac{T_{opt} - T_{min}}{T_c - T_{opt}}} \right]^{ct} \quad (15)$$

$$S_T(t, T) = 0 \quad T_c < T(t) < T_{min}$$

This equation leads to a typical bell shaped temperature response curve. If there is no data available to determine the fitting parameter ct , its value can be set to 1 (Yan and Hunt, 1999; Yin and van Laar, 2005).

5. Actual Root Distribution

The actual root depth is used to calculate the potential pattern of the root length density distribution using the root length density distribution models. The potential increase in the rooting depth, calculated as a function of either time or thermal time, is reduced using the minimum of the six stress factors, producing the actual increase in the rooting depth. In the one-dimensional model (i.e., HYDRUS-1D), the stress factor values in the last node containing roots are considered for the reduction.

A potential increase in the root length distribution (RLD_{gp}) is calculated as the difference between the root length distribution at the current and previous time steps. An increase in the root length density in each node can be reduced or increased due to root senescence or hydrotropism, respectively.

The *root senescence* (Sen) is calculated according to Jones et al. (1991):

$$Sen = rate_d \cdot RLD_{gp} \cdot [1 + \max(1 - \theta_f, 1 - S_{Ae})] \quad (16)$$

where $rate_d$ is the scaling factor defining the influence of root senescence (0-1). This approach assumes that root senescence can be increased due to low water availability or poor aeration.

The user can also consider the phenomena of *hydrotropism*. When hydrotropism is to be considered during the simulation, the HYD value has to be set to 1 (otherwise to 0). In the one-dimensional approach, the hydrotropism can only be used to increase the root length density distribution in wet parts of the root zone. Within the current implementation, this phenomenon is evaluated as a function of the fractional water content (θ_f , eq. (11)). An increase of the potential root length density due to hydrotropism ($HydTr$) is calculated as follows:

$$HydTr = rate_g \cdot RLD_{gp} \cdot \theta_f^3 \quad (17)$$

where $rate_g$ is a scaling factor (0-1) defined by the user. The potential increase in the root length density distribution (RLD_{gp}) is multiplied by the third power of θ_f , which gives nodes with a θ_f value close to 1 a higher weight than to those with a value close to 0. A value of θ_f close to 1 indicates a high water availability. When the scaling factor $rate_g$ is set to 1, in nodes with θ_f close of 1, the same amount of the potential increase in the root length density is added due to hydrotropism. By defining the value of $rate_g$, the influence of hydrotropism can be adjusted manually.

The actual root length density distribution (RLD_{beta}) is calculated as:

$$\begin{aligned} RLD_{ga} &= (RLD_{gp}) - Sen + HydTr \\ RLD_{beta}(t) &= RLD_{beta}(t-1) + RLD_{ga} \end{aligned} \quad (18)$$

where RLD_{ga} represents an actual increase in the root length density, and Sen and $HydTr$ describe a decrease and an increase in the root length density due to root senescence and hydrotropism, respectively.

The **death of roots** after reaching maturity can be calculated in two different ways when the time-dependent root growth is considered. By setting the parameter RSC to 1, the user can specify cumulative time (t_{RD}), at which the roots are considered to be dead. Between this point and time when plants reach maturity, the roots are dying at a constant death rate:

$$Sen = RLD_D \cdot \left(\frac{t - t_M}{t_{RD} - t_M} \right)^3 \quad (19)$$

where RLD_D is the actual distribution of the root length density at maturity (t_M).

By setting RSC to 2, the death of roots after reaching maturity is calculated using the root senescence approach:

$$Sen = (t_i - t_{i-1}) \cdot rate_{Death} \cdot RLD_D \cdot [1 + \max(1 - \theta_f, 1 - S_{Ae})] \quad (20)$$

The Sen value is added at each time step after reaching maturity to values at previous time steps. To calculate the actual root length density distribution at each time step, the sum is subtracted from RLD_D . When the root growth is considered to be dependent on thermal time, only the second approach is applicable.

6. Calculation Steps

Figure 3 summarizes the calculation procedure of the new modeling approach of root growth. The static stress factors are calculated just one time at the beginning of the simulation. The dynamic stress factors are updated at each time step. In the last but one step (Fig. 3), the accumulation of roots in soil layers with higher water availability is considered. This can lead to a further increase in the actual increase due to hydrotropism (see hydrotropism).

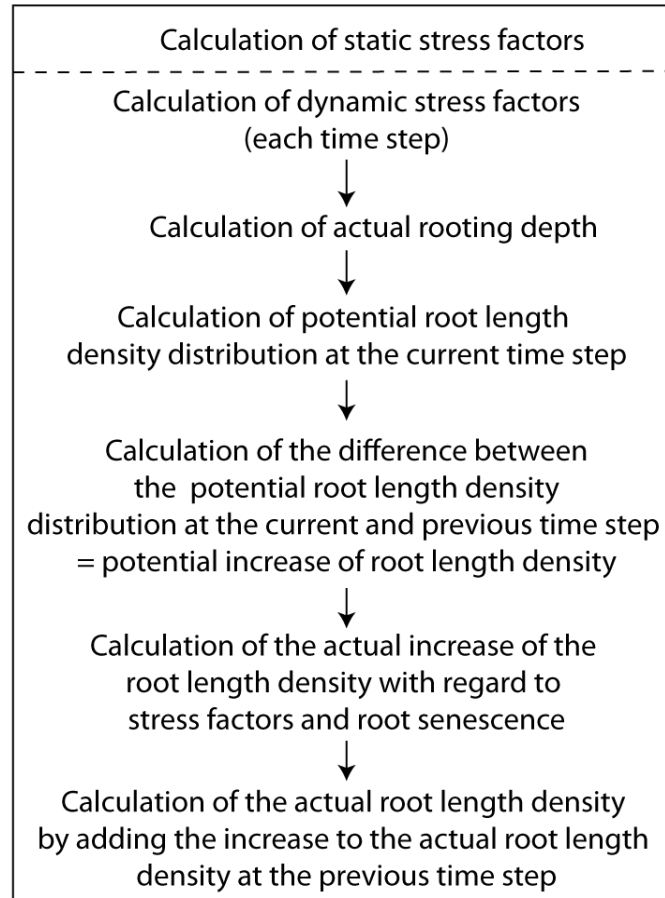


Figure 3. Scheme of the calculation procedure.

7. Detailed Description of the Root.in File for HYDRUS-1D

Table 3 below gives a detailed description of the Root.in file and Table 5 provides an example of this file for the demonstrative example described in the text below.

Table 3. Description of the Root.in file for HYDRUS-1D.

Record	Type	Variable	Description
1-8	-	-	Comment lines.
9	Integer	<i>BDYN</i>	=1: the bulk density stress factor is considered; =0: is not
9	Integer	<i>FYN</i>	=1: the coarse fragment stress factor is considered; =0: is not
9	Integer	<i>TYN</i>	=1: the temperature stress factor is considered; =0: is not
9	Integer	<i>AYN</i>	=1: the aluminum toxicity stress factor is considered; =0: is not
9	Integer	<i>CYN</i>	=1: the calcium deficiency stress factor is considered; =0: is not
9	Integer	<i>SYN</i>	=1: the soil strength stress factor is considered; =0: is not
9	Integer	<i>AEYN</i>	=1: the aeration stress factor is considered; =0: is not
9	Integer	<i>RSYN</i>	=1: root senescence is considered; =0: is not
10-13	-	-	Comment lines.
14	Integer	<i>RDM</i>	Root distribution function =1: Zuo et al. (2004) =2: other =3: Wu et al. (1999) =4: Vrugt et al. (2001) =5: Jones et al. (1991)
14	Integer	<i>HYD</i>	=1: hydrotropism is considered; =0: is not
15-18	-	-	Comment lines.
19	Real	<i>PZ</i>	Parameter of the Vrugt function, has to be specified if <i>RDM</i> =4
19	Real	<i>Zv</i>	Parameter of the Vrugt function, has to be specified if <i>RDM</i> =4
20-24	-	-	Comment lines.
25	Real	<i>RDX</i>	Maximum rooting depth
25	Real	<i>PD</i>	Planting depth (d_p)
25	Real	<i>TBS</i>	Base temperature for root growth (T_{min}) (°C)
25	Integer	<i>TOP</i>	Optimum temperature for root growth (T_{opt}) (°C)
25	Integer	<i>TA</i>	=0: temperature stress calculated according to Jones et al. (1991) (eq. 11) =1: temperature stress calculated using the bell shaped function (eq. 15)
25	Real	<i>CAA</i>	Calcium saturation (%) below which root growth is reduced (Ca_A)
25	Real	<i>CAX</i>	Calcium saturation (%) below which root growth is negligible (Ca_X)
25	Real	<i>ALA</i>	Aluminum saturation (%) below which root growth is unaffected (Al_A)
25	Real	<i>ALX</i>	Aluminum saturation (%) above which root growth is negligible (Al_X)
25	Real	<i>SFT</i>	Fraction of normal root growth when the pore space is saturated (0-1) (S_{FT}) =0: no growth in saturated soil =1: no effect of flooding on root growth
25	Integer	<i>CW</i>	=0: critical water filled porosity is calculated via particle distribution (eq. 12) =1: critical water filled porosity is set to <i>CWFP</i>

25	Real	<i>CWFP</i>	User defined critical water filled porosity
26	-	-	Comment line.
27	Real	TC	Ceiling temperature for the bell shaped temperature stress approach (T_c)
27	Real	Ct	Parameter for flexibility of the bell shaped temperature response curve (ct) =1: if no data for fitting this parameter is available
28-31	-	-	Comment lines.
32	Real	<i>SAN</i>	Sand content of the soil (%), measured as a percent by weight
32	Real	<i>SIL</i>	Silt content of the soil (%), measured as a percent by weight
32	Real	<i>BD</i>	Bulk density of the fine earth fraction (mg/m^3)
32	Real	<i>ROK</i>	Coarse fragments as a fraction of soil volume (0-1)
32	Real	<i>SMB</i>	Sum of bases (cmol/kg); set as default when <i>AYN</i> and <i>CYN</i> =0
32	Real	<i>EAL</i>	Extractable aluminum (cmol/kg); set as default when <i>AYN</i> =0 (Al_E)
32	Real	<i>CA</i>	Exchangeable calcium (cmol/kg); set as default when <i>CYN</i> =0
32	Real	<i>ULh</i>	Upper limit of the pressure head for the plant extractable soil water (θ_u) for the fine earth fraction (enter pressure head as a positive value)
32	Real	<i>LLh</i>	Lower limit of the pressure head for the plant extractable soil water (θ_L) for fine earth fraction (enter pressure head as a positive value)
32-40	-	-	Comment lines.
41	Integer	<i>RGR</i>	=1: time dependent root growth; =0: root growth depends on thermal time
41	Real	<i>drate</i>	Scaling factor to define the influence of root senescence ($rate_d$) (0-1)
41	Real	<i>grate</i>	Scaling factor to define the influence of hydrotropism ($rate_g$) (0-1)
42-49	-	-	Comment lines.
50	Integer	<i>TDT</i>	=1: sine function for time dependent root growth is used; =2: Verhulst-Pearl logistic growth function is used
50	Real	<i>DAP</i>	Time after planting (for <i>TDT</i> =1) (t_p)
50	Real	<i>DTM</i>	Time to maturity (for <i>TDT</i> =1) (t_M)
50	Real	<i>DTP</i>	Time to planting (for <i>TDT</i> =1) (Δt_p)
50	Real	<i>DRD</i>	Time to death of the root system (for <i>TDT</i> =1)
50	Real	<i>tRMin</i>	Initial root growth time (for <i>TDT</i> =2)
50	Real	<i>tRHarv</i>	Harvest time (for <i>TDT</i> =2)
50	Real	<i>tRPeriod</i>	Time period (for <i>TDT</i> =2)
50	Integer	<i>ir</i>	1: root growth parameter in Verhulst-Pearl logistic growth function is specified by users, 0: it is calculated using HYDRUS-1D standard code
50	Real	<i>r</i>	value of root growth parameter in Verhulst-Pearl logistic growth function when $ir=1$
51-52	-	-	Comment lines.
53	Integer	<i>RSC</i>	=1: roots are dying until <i>DRD</i> is reached; =0: root growth ends at Δt_M and rooting depth remains constant
54-58	-	-	Comment lines.
59	Real	<i>TDM</i>	Maximum temperature for the development of a particular crop, when <i>RGR</i> =0 (T_{Max})
59	Real	<i>TDB</i>	Basal temperature for the development of a particular crop, when <i>RGR</i> =0 (T_{Min})
59	Real	<i>TTH</i>	Thermal time threshold for the root development, when <i>RGR</i> =0 (tt_M)
59	Real	<i>TG</i>	Empirical growth factor, when <i>RGR</i> =0

8. Detailed Description of the Root.out File for HYDRUS-1D

Table 4 below gives a detailed description of the Root.out file. The Root.out file provides profile information about the root length density and stress factors at different points in time.

Table 4. Description of the Root.out file for HYDRUS-1D.

Variable	Description
<i>RLD</i>	Root length density
<i>SCa</i>	Calcium deficiency stress factor
<i>SAI</i>	Aluminum toxicity stress factor
<i>SBD</i>	Bulk density stress factor
<i>SCF</i>	Coarse fragments stress factor
<i>SST</i>	Soil strength stress factor
<i>SAE</i>	aeration stress factor
<i>ST</i>	temperature stress factor

9. A Demonstrative HYDRUS-1D Example

Figure 4 shows the simulation results for the development of the root system under drought conditions with the parameter setting specified in Table 5. The soil profile is homogeneous consisting of the first material described in Table 5. The soil hydraulic parameters were estimated using the Rosetta module of HYDRUS-1D from the textural information. The soil consists of approximately 50 % silt, 40 % clay, 10 % sand. The atmospheric boundary conditions is used at the soil surface. The potential evaporation and transpiration rates increase stepwise at the beginning of the simulation and remain at a constant rate during the rest of the simulation. Irrigation takes place every few days. A free drainage boundary condition was used at the bottom of the soil profile.

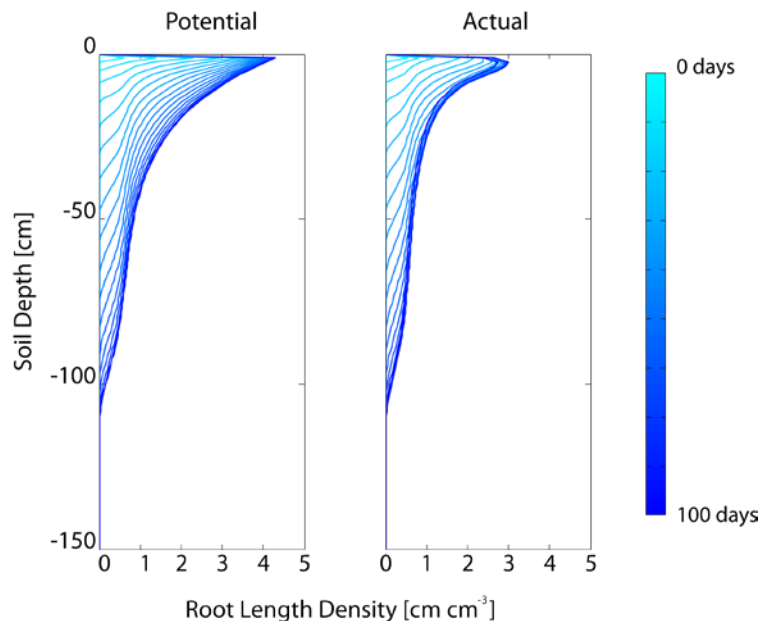


Figure 4. Simulated potential and actual root length density distributions under drought conditions.

Figure 5 shows the results for the same settings as above, but with an increase in water extraction due to a higher transpiration rate. Additionally, irrigation values were reduced to produce stronger drought conditions. The results show that due to reduced water availability, the actual development of the root system is reduced. The root length density is reduced in soil depths, where the soil gets very dry. An increase in the potential transpiration rate leads to a greater decrease in the actual root length density distribution due to an increased stress.

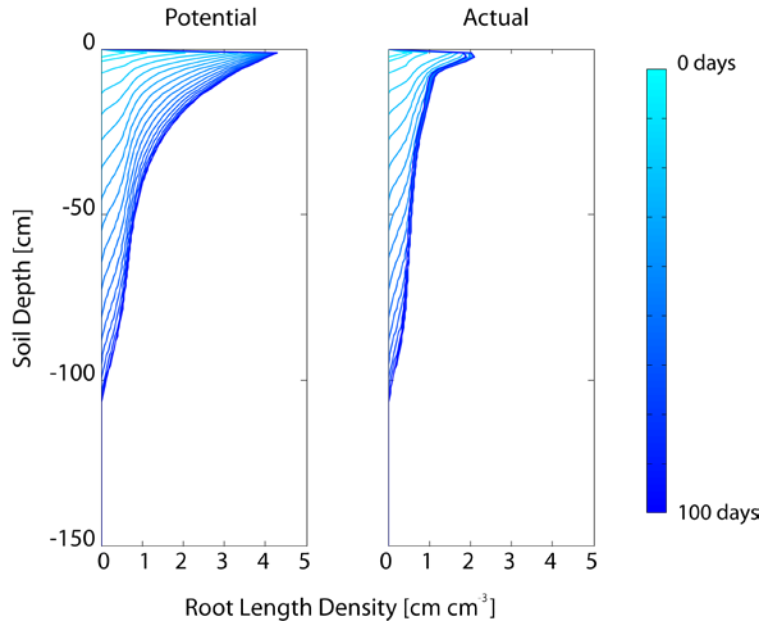


Figure 5. Simulated potential and actual root length density distributions under increased drought conditions.

The results also show that the simulated rooting depth is reduced compared with to the specified potential maximum rooting depth ($RDX=120$ cm) defined in the input file. Note that the potential root length density distributions shown in the graphs already consider the reduced rooting depth due to stress factors. The reduction in the rooting depth is the result of the soil strength factor ($SYN=1$) and the aeration stress factor ($AEYN=1$). In this case, no further stress factors were considered, which could lead to a reduction in the rooting depth.

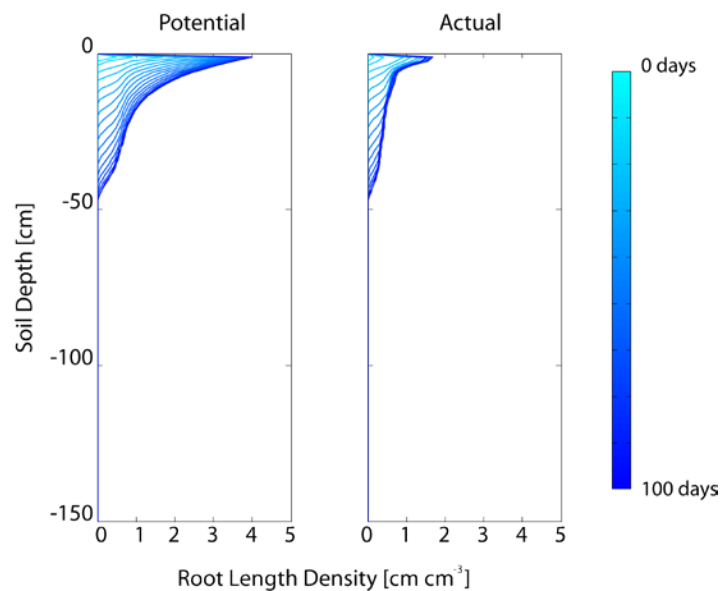


Figure 6. Simulated potential and actual root length density distributions under increased drought conditions and when considering the influence of texture and bulk density on the rooting depth.

Figure 6 shows the results for the same settings, except that the effects of texture and bulk density of moist soil ($BDYN=1$) were considered. The results show a strong reduction in the rooting depth due to the considered effects of the bulk density. Together with the low water availability, these settings produced an undeveloped root system.

Figure 7 shows the results for the same settings, except with higher water contents (and thus more water being available to plant roots), which produced a root system with a greatly reduced rooting depth, but with a higher root length density compared to that shown in Figure 6.

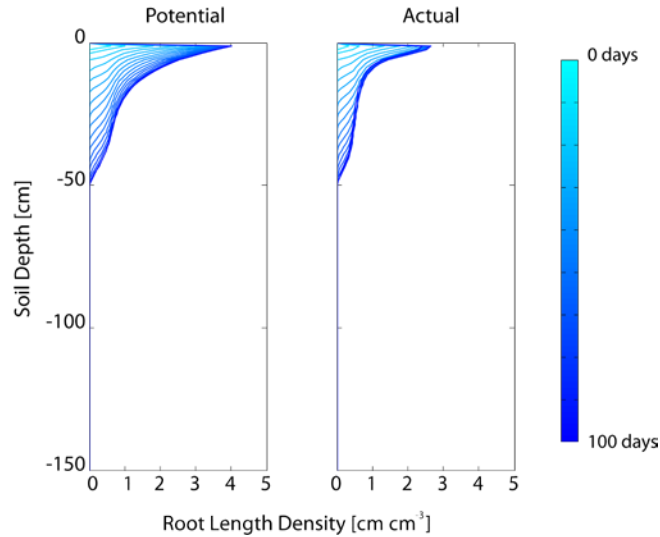


Figure 7. Simulated potential and actual root length density distributions when considering the influence of texture and bulk density on the rooting depth and with higher water contents.

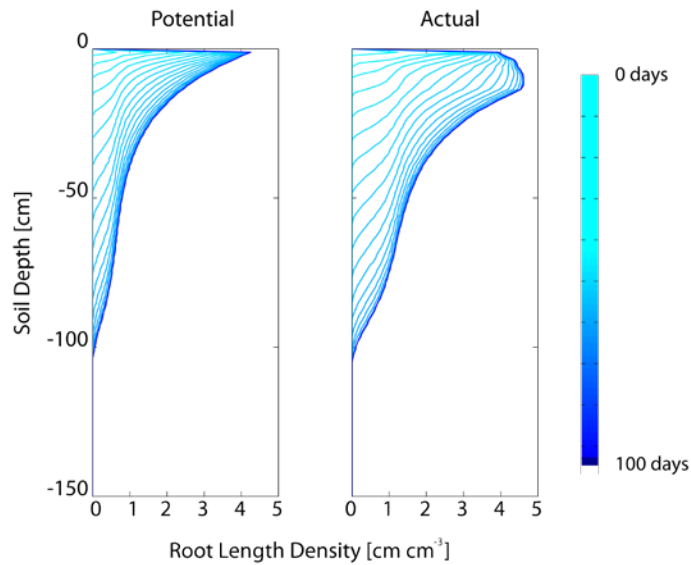


Figure 8. Simulated potential and actual root length density distributions when additionally considering the influence of hydrotropism.

Figure 8 shows simulated results when hydrotropism was considered ($HYD=1$) together with an increase in water availability due to a higher irrigation amount and frequency and a reduced potential transpiration. The results show an increase in the root length density in soil depth with more available water.

Figure 9 shows simulated results for a root system with the same settings as before, but with different soil horizons. The second material described in Table 5 is located between 20 and 50 cm. Although the hydraulic conductivities of the two soil materials were almost the same, the second material consists of a higher amount of silt and sand and less clay compared to the surrounding material. The results show that due to different properties of the additional soil horizon, which affects water availability and oxygen supply, the development of the root system is different in this soil horizon. Note that the absolute values of the root length density are not important for the distribution of the root water uptake throughout the soil profile, since the root length density function is always normalized.

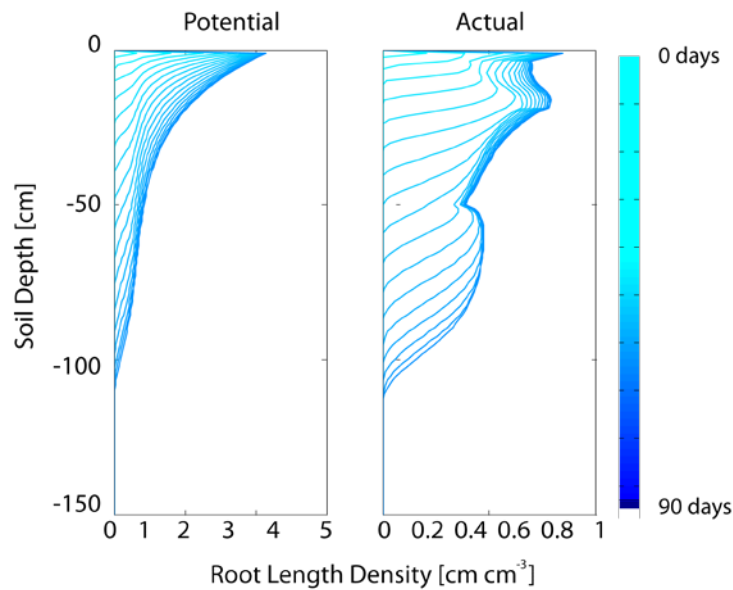


Figure 9. Simulated potential and actual root length density distributions for a soil system with two different soil materials. The second material is embedded between two layers of the same material.

Figure 10 shows simulation results for the same conditions as in Figure 9, except that the simulation was extended to 200 days. After reaching maturity after 90 days, the root system started dying because of root senescence.

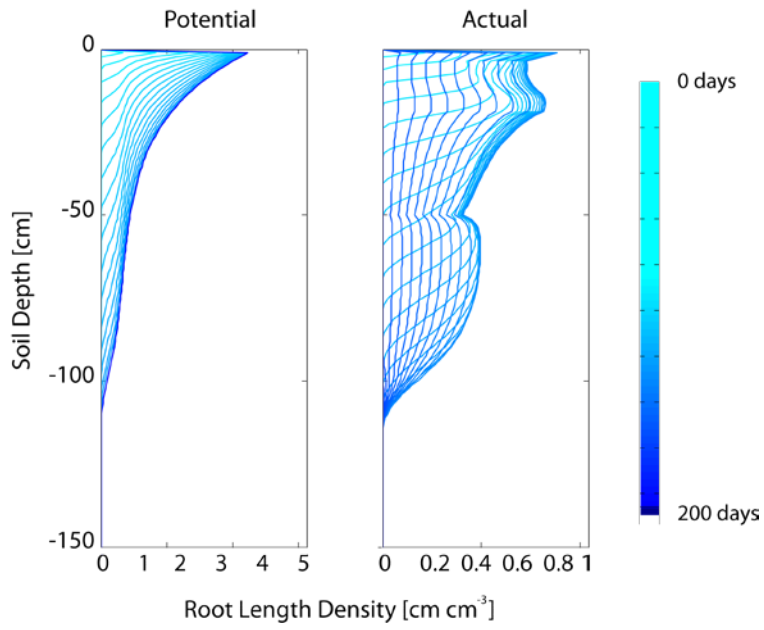


Figure 10. Simulated potential and actual root length density distributions for a soil system with two different soil materials as in Figure 9. After reaching the maximum growth stage, the root system starts to die.

Table 5. Input parameter settings for the demonstrative HYDRUS-1D example.

```

! Input file for advanced root zone calculation
! To use this option set the root depth specification in the GUI to Time-Variable Boundary
! Conditions. Set the iRootDepthEntry in the Selctor.In-File to 3.
****
! Choose which stress factors should be considered for limiting root development
! by setting the following values to 0 (no consideration) or 1 (consideration)
****
BDYN   FYN   TYN   AYN   CYN   SYN   AEYN  RSYN
  0     0     0     0     0     1     1     1
****
! Specify which root density distribution model should be used and whether you want to regard
hydrotropism
****
RDM   HYD
  2     0
****
! When RDM = 4; Specify parameter for Vrugt-function:
****
PZ     Zv
  6     0
****
! Specify parameters needed for describing root development. Keep parameter values at default
when no
! Consideration of these stress factor is chosen
****
RDX   PD   TBS   TOP   TA   CAA   CAX   ALA   ALX   SFT   CW   CWFP
120   0.001 19.0  21.0  0   15.0  0   43.0  90.0  0   1   0.9
  TC   Ct
  30   1
****
! Additional material information, set as many as materials
****
      SAN  SIL  BD  ROK  SMB  EAL  CA   ULh  LLh
      11.6 50.4 1.53 0  10.1  0   18.7  325  8000
      23.5 63.8 1.29 0  10.1  0   5.60  325  8000
****

```

Root Growth

```

****
! Specify which type of root growth should be used: time dependent: 1, thermal-time dependent: 2
****
RGR   drate  grate
  1     0.1    1
****
! When RGR = 1, specify the number of days after planting and how many days to maturity of
! the crop are left at the start of the simulation. If the planting takes place after the
! start of the simulation set DAP to 0 and specify the days to planting at the start of the
! simulation (DTP), specify then the days to maturity of the crop upon the time of planting.
! If simulation starts with planting or the planting already took place, then set DTP to 0.
****
TDT   DAP   DTM   DTP   DRD   tRMin   tRHarv   tRPeriod   ir   r
  1     0     90     0     120     0       90       365       1   0.366
****
RSC
  2
****
! When RGR = 2, specify the maximum and minimum temperature for development for the particular
! crop in °C, set cumulative thermal time, at which root growth stops
****
TDM   TDB   TTH   TG
34.0   1.0  1000  0.02

```

Implementation into HYDRUS-2D

The above-described stress factor approach was also implemented into the HYDRUS-2D code. At present, only the time-dependent growth functions are used to calculate a potential increase of the rooting depth. The thermal-time-dependent root growth approach is not yet implemented. Only the two-dimensional root distribution function of Vrugt et al. (2001) is used to describe the potential two-dimensional root length density distribution.

The calculation of the actual increase in the rooting depth differs in the two-dimensional model from the one in the one-dimensional model. In the two-dimensional code, the minimum stress factors in all nodes containing roots are averaged to give an average stress factor for the whole root system. This average stress factor is used to reduce the potential increase in the r_m and z_m parameters between two time steps. These parameters describe the maximum rooting lengths in the radial and vertical directions.

No attempts have been made to implement hydrotropism into the 2D code. The death of the root system after reaching the maximum growth stage is calculated by using the second approach described for the 1D model.

10.Detailed Description of the Root.in File for HYDRUS-2D

Table 6 below gives a detailed description of the Root.in file and Table 7 provides an example of this file for the demonstrative example described in the text below.

Table 6. Description of the Root.in file for HYDRUS-2D.

Record Type	Variable	Description	
1-2	-	-	Comment lines.
3	Logical <i>lHoriz</i>	The Vrugt function is used also for horizontal distribution	
3	Logical <i>lRootGrowth</i>	The rooting depth (and the horizontal extent of the root zone) is time variable, described using Verhulst-Pearl logistic growth function	
3	Integer <i>nPlant</i>	Number of plants	
3	Integer <i>lRootEF</i>	The new root growth approach is used	
3	Logical <i>lrDeath</i>	The <i>death of roots</i> after reaching maturity is calculated.	
4	-	-	Comment line
5	Real <i>rZm</i>	The maximum rooting lengths in the <i>z</i> - direction [L]	
5	Real <i>rZO</i>	The depth of the maximum uptake intensity [L]	
5	Real <i>rA</i>	The empirical factor p_z	
			The following two lines are given only when <i>lHoriz</i> = .true.
6	-	-	Comment line
7	Real <i>rRm</i>	The maximum rooting lengths in the <i>x</i> - direction [L]	
7	Real <i>rRO</i>	The radius of the maximum uptake intensity [L]	
7	Real <i>rB</i>	The empirical factor p_x	
7	Real <i>rCenter(nPlant)</i>	<i>x</i> -coordinate of the center in the horizontal direction (for <i>nPlants</i>).	
			The following six lines are given only when <i>lRootGrowth</i> = .true.
8	-	-	Comment line
9	Integer <i>iRFak</i>	Method to calculate the root growth factor, <i>r</i> . = 0; the root growth factor is calculated from given data [<i>xRMed</i> , <i>tRMed</i>]. = 1; the root growth factor is calculated based on the assumption that 50% of the rooting depth, $(xRMax+xRMin)/2.$, is reached at the midpoint of the growing season, $(tRMin+tRHarv)/2.$	
9	Real <i>tRMin</i>	Initial time of the root growth period [T].	
9	Real <i>tRMed</i>	Time of known rooting depth (set equal to zero if <i>iRFak</i> =1) [T]	
9	Real <i>tRHarv</i>	Time at the end of the root water uptake period [T]	
9	Real <i>tRPeriod</i>	Time period at which the growth function repeat itself.	
10	-	-	Comment line
11	Real <i>rZMin</i>	Initial value of the rooting depth at the beginning of the growth period (recommended value = 1 cm) [L]	
11	Real <i>rZMed</i>	Value of known rooting depth (set equal to zero if <i>iRFak</i> =1) [L]	

11	Real	<i>rZMax</i>	Maximum rooting depth, which may be reached at infinite time [L] The following two lines are given only when <i>lHoriz</i> = .true.
12	-	-	Comment line
13	Real	<i>rRMin</i>	Initial value of the rooting radius at the beginning of the growth period (recommended value = 1 cm) [L].
13	Real	<i>rRMax</i>	Maximum rooting radius, which may be reached at infinite time [L].
14	-	-	Comment line
15	Integer	<i>BDYN</i>	=1: the bulk density stress factor is considered; =0: is not
15	Integer	<i>FYN</i>	=1: the coarse fragment stress factor is considered; =0: is not
15	Integer	<i>TYN</i>	=1: the temperature stress factor is considered; =0: is not
15	Integer	<i>AYN</i>	=1: the aluminum toxicity stress factor is considered; =0: is not
15	Integer	<i>CYN</i>	=1: the calcium deficiency stress factor is considered; =0: is not
15	Integer	<i>SYN</i>	=1: the soil strength stress factor is considered; =0: is not
15	Integer	<i>AEYN</i>	=1: the aeration stress factor is considered; =0: is not
15	Integer	<i>RSYN</i>	=1: root senescence is considered; =0: is not
16	-	-	Comment line
17	Real	<i>TBS</i>	Base temperature for root growth (T_{min}) (°C)
17	Real	<i>TOP</i>	Optimum temperature for root growth (T_{opt}) (°C)
17	Real	<i>CAA</i>	Calcium saturation (%) below which root growth is reduced (Ca_A)
17	Real	<i>CAX</i>	Calcium saturation (%) below which root growth is negligible (Ca_X)
17	Real	<i>ALA</i>	Aluminum saturation (%) below which root growth is unaffected (Al_A)
17	Real	<i>ALX</i>	Aluminum saturation (%) above which root growth is negligible (Al_X)
17	Real	<i>SFT</i>	Fraction of normal root growth when the pore space is saturated (0-1) (S_{FT}) =0: no growth in saturated soil =1: no effect of flooding on root growth
17	Real	<i>CW</i>	=0: critical water filled porosity is calculated via particle distribution (eq. 12) =1: critical water filled porosity is set to <i>CWFP</i>
17	Real	<i>CWFP</i>	User defined critical water filled porosity
17	Real	<i>ULh</i>	Upper limit of the pressure head for the plant extractable soil water (θ_U) for the fine earth fraction (enter pressure head as a positive value)
17	Real	<i>LLh</i>	Lower limit of the pressure head for plant extractable soil water (θ_L) for fine earth fraction (enter pressure head as a positive value)
18	-	-	Comment line
19	Real	<i>SAN</i>	Sand content of the soil (%), measured as a percent by weight
19	Real	<i>SIL</i>	Silt content of the soil (%), measured as a percent by weight
19	Real	<i>BD</i>	Bulk density of the fine earth fraction (mg/m ³)
19	Real	<i>ROK</i>	Coarse fragments as fraction of soil volume (0-1)
19	Real	<i>SMB</i>	Sum of bases (cmol/kg); set as default when <i>AYN</i> and <i>CYN</i> =0
19	Real	<i>EAL</i>	Extractable aluminum (cmol/kg); set as default when <i>AYN</i> =0
19	Real	<i>CA</i>	Exchangeable calcium (cmol/kg) ; set as default when <i>CYN</i> =0
20	-	-	Comment line
21	Real	<i>drate</i>	Scaling factor to define the influence of root senescence ($rate_d$) (0-1)
22	-	-	Comment line
23	Integer	<i>TA</i>	=0: temperature stress calculated according to Jones et al. (1991) =1: temperature stress calculated with the bell shaped function

23	Real	TC	Ceiling temperature for the bell shaped temperature stress approach (T_c)
23	Real	iCt	Parameter for flexibility of the bell shaped temperature response curve (ct) =1: if no data for fitting this parameter is available
24	-	-	Comment line
24	Integer	TDT	=1: Verhulst-Pearl logistic growth for time dependent root growth is used; =2: sine function is used ($iTDT$)
24	Real	Tm	Time to maturity (for $TDT=2$) (t_M)
24	Integer	ir	=1: root growth parameter in the Verhulst-Pearl logistic growth function is specified by users, =0: it is calculated using HYDRUS-1D standard code ($iRGR$)
24	Real	r	value of root growth parameter in the Verhulst-Pearl logistic growth function when $ir=1$ (RGR)

10. A Demonstrative HYDRUS-2D Example

Figure 11 shows the results of the potential and actual root system development simulated by HYDRUS-2D for the parameter settings specified in Table 7. The considered soil is homogeneous consisting of approximately 50 % sand, 30 % clay, and 20 % silt. The soil hydraulic parameters were estimated using the Rosetta module of HYDRUS-2D and the soil textural information given in Table 7. The atmospheric boundary condition was defined using the constant potential evaporation and transpiration rates of 0.1 mm/d and 5 mm/d, respectively, throughout the whole simulation time. Irrigation was considered to take place on days 1, 6, 8, 17, and 42, with the amount of 10 mm each day on the entire soil surface. A free drainage boundary condition was used at the bottom of the soil profile.

Only one plant in the middle of the domain was considered. The roots were considered to grow for 45 days. After reaching the maximum growth stage, the root system was considered to start dying due to root senescence. The reduction of the rooting depth is a result of the influence of the soil strength factor ($SYN=1$), the aeration stress factor ($AEYN=1$), and the effects of texture and bulk density of moist soil ($BDYN=1$).

Table 7. Input parameter settings for the demonstrative HYDRUS-2D example.

```

*** Root Distribution Function Input *****
Horizontal distribution  RootGrowth nPlant  lRootEF  lrDeath
t                      t          1          t          t
rZm      rZ0      rA
100      20      1
rXm      rX0      rB      rCenter      rCenter
30       0       1       25
iRFak    tRMin    tRMed    tRHarv    tRPeriod
1        5        0        45        60
rZMin    rZMed    rZMax
5        0      80
rRMin    rRMax
5        75
BDYN    FYN    TYN    AYN    CYN    SYN    AEYN    RSYN
1       0     0     0     0     1     1     1
TBS     TOP    CAA    CAX    ALA    ALX    SFT    CW    CWFP    ULh    LLh
19      21    15    0     43    90    0     1    0.9    325    8000
SAN     SIL    BD    ROK    SMB    EAL    CA
54.4   18.4  1.51  0     10.1  0     8.1
drate
0.1
TA     TC    iCT
1     30    1
TDT    Tm    ir    r
2     60    1    0.334
*** End of the Root.in File *****

```

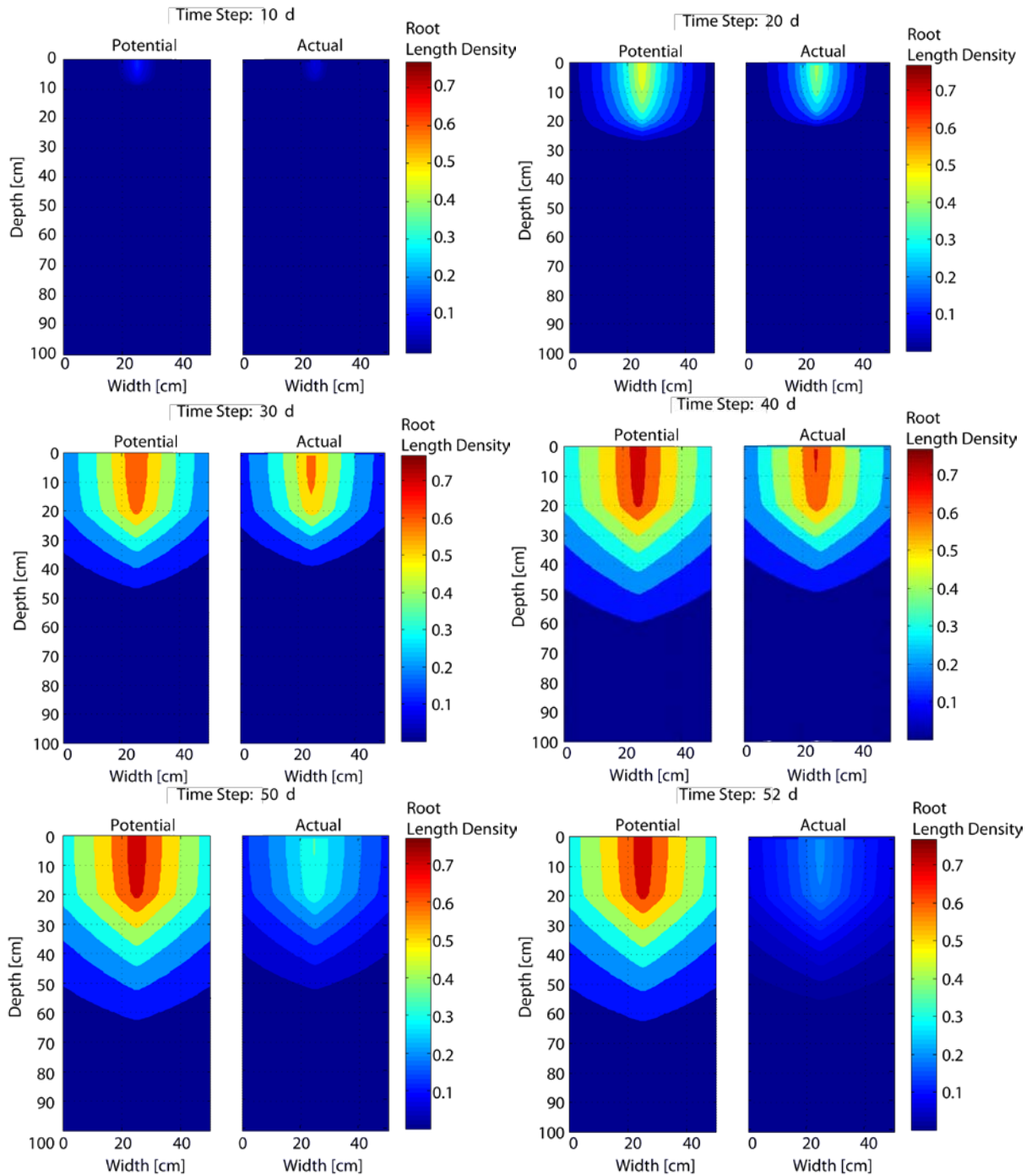


Figure 11. Results of the potential and actual root system development for different times (simulated by HYDRUS-2D) when irrigation is applied at the entire soil surface.

Figure 12 shows the results for the same soil, the same stress factor settings, and the same simulation time as above, except for a few changes in the root growth settings. In this case the root system needs the entire simulation time to reach maturity. Additionally, a spatially asymmetric irrigation was applied at the soil surface. Irrigation was applied with a rate of 2 mm/d between days 30 and 50 only in the top left corner (the first 10 cm of the soil surface)

while the rest of the soil surface remained un-irrigated and exposed only to evaporation. Potential evaporation was set to of 0.1 mm/d from the beginning until day 15, to 1 mm/d between days 16 and 18, and to 2 mm/day from day 19 until the end of the simulation. Potential transpiration was set to 0.1 mm/d between the first day and day 11. From day 12 to day 29 potential transpiration was set to 1 mm/d and to 2 mm/d from day 30 until the end of simulation. The results show that this asymmetric irrigation produced an unequal development of the root system. The root system is more developed on the left hand side of the transport domain where more water is available compared to the right hand side of the transport domain where less water is available. Again, the results are compared to the potential root length density, which represents the case when the influence of the environmental factors is neglected.

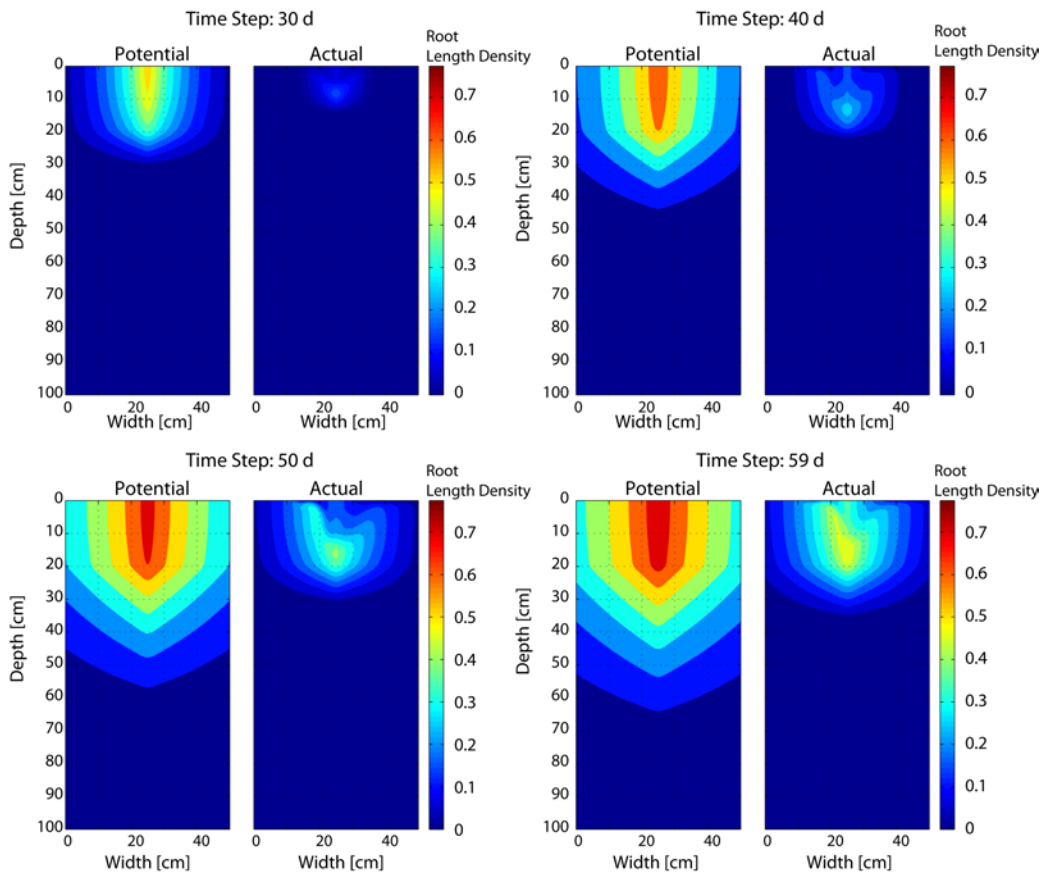


Figure 12: Results of the potential and actual root system development for different times (simulated by HYDRUS-2D) when irrigation is applied in the top left corner.

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