

Chapter 10: Root Water Uptake: Root_Water_Uptake

Module

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There are two methods commonly used to describe water uptake by plant roots. Models like ROOTSIMU (Hoogenboom and Huck, 1986) require information on plant and root development because root activity and root water uptake depend not only on the soil and atmosphere environment but also on plant status, and the plant's ability to extract water and to grow roots. Other models like SWMS_2D (Šimůnek et al., 1994) and CERES-Maize (Jones and Kiniry, 1986) do not require detailed information on the growth and development of the plant canopy and roots. Root distribution either does not change in time or changes independently of shoot status. Both of these approaches are available in 2DSOIL. The module **Water_Uptake01** uses plant status information extensively and requires an additional module that will generate shoot-dependent variables that control water uptake and root growth. Module **Water_Uptake02** does not simulate root development and so does not need the plant status information. Root densities must be supplied as input data, however.

10.1 Plant status dependent model: Water_Uptake01

This module is based on the root activity model developed by Acock and incorporated into the soybean crop simulator GLYCIM (Acock and Trent, 1991). In this model, root growth is driven by carbon supplied by the above ground plant. Carbon partitioning and water uptake are determined by leaf water and soil water potentials. If water in the root zone becomes limiting, the shoot can divert some carbon normally used for shoot and leaf growth to the roots to increase root growth into wetter areas of the soil. The model generates a relationship between the potential transpiration rate E_c and leaf water potential ψ_L for each time step. The shape of the

relationship between ψ_L and E_c reported for a variety of plants (Stoker and Weatherly, 1971; Hailey et al., 1973; Bunce, 1978) is shown in Fig. 10.1. The model assumes that characteristic points A, B, C, D separate intervals of different levels of carbon partitioning between the shoot and the root in the following way:

(1) At low transpiration demands, between points A and B , mature roots and new roots added using carbon "left over" after shoot growth is satisfied, can extract sufficient water. The slope of the relationship between leaf water potential and potential transpiration remains constant, at the level $\Psi_{L,0}$, and there is no diversion of additional carbon from the shoot to the root. In other words, until the leaf water potential reaches $\Psi_{L,0}$ the plant can adjust leaf water potential to maintain water uptake as the potential transpiration rate changes.

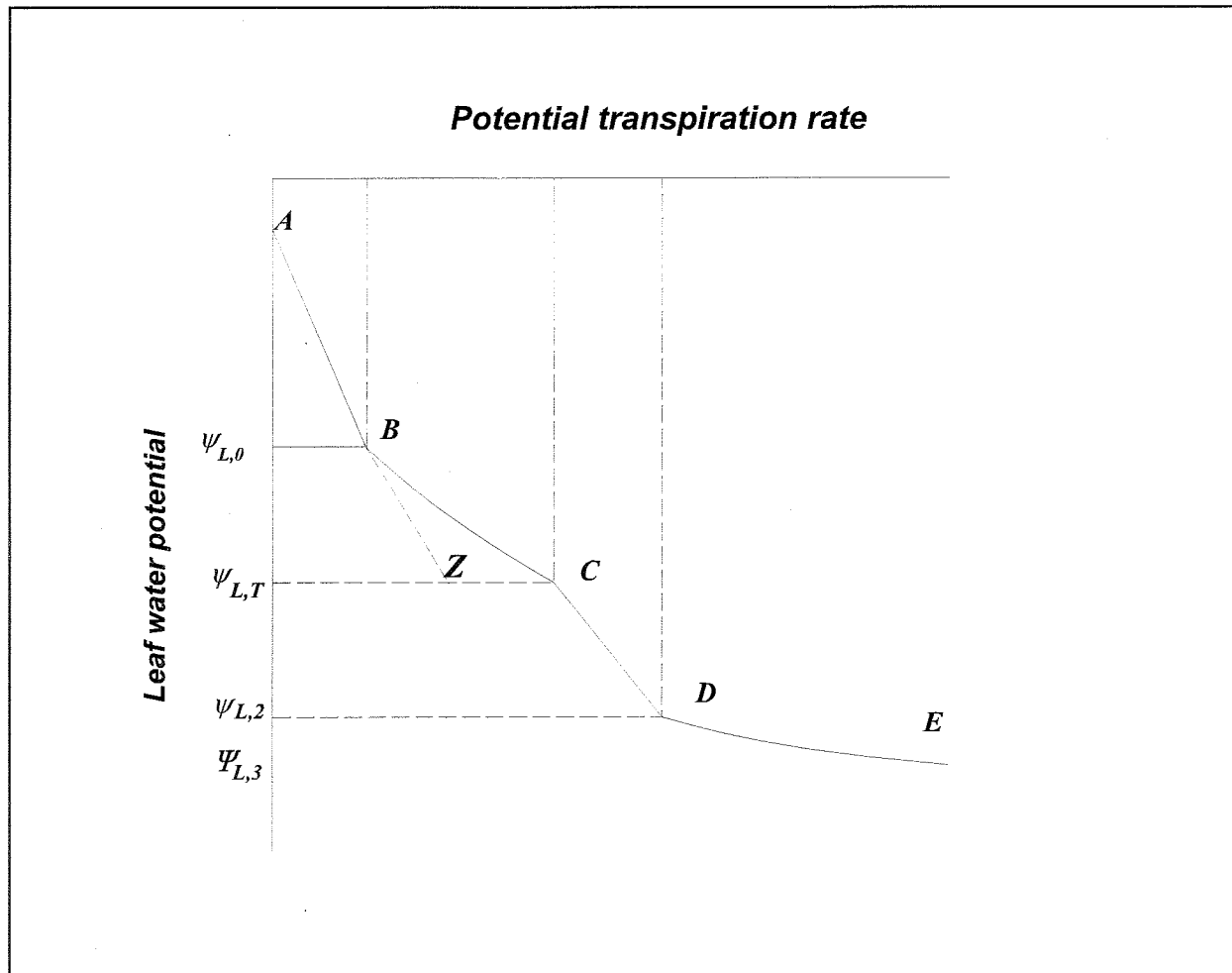


Figure 10.1 Typical relationship between potential transpiration rate and water potentials in the soil-plant-atmosphere system. Here $\psi_{L,0}$ is the leaf water potential at low transpiration rates when there is no diversion of carbon to the roots, below this potential, the leaf water potential begins to decrease as the potential evaporation rate increases, $\psi_{L,T}$ is the leaf water potential when all available carbon goes to root growth (C), $\psi_{L,2}$ is the point at which the stomates begin to close (D), and $\psi_{L,3}$ is the point at which water uptake becomes negligible (E).

(2) At intermediate transpiration demands, between points B and C, the plant must decrease its leaf water potential in order to increase the leaf-soil water potential gradient. Simultaneously, additional carbon is diverted to the roots to increase the pool of young roots that have a lower resistance to water uptake. Beginning at point C, the plant uses all available carbon for root growth and the shoot no longer grows. The line segment Z-C represents additional water uptake that results when all available carbon is used to grow roots.

(3) At high transpiration demands, between points *C* and *D*, the roots are supplied with the maximum amount of carbon available and shoot growth stops. As transpiration demand increases, both leaf water potential ψ_L and leaf turgor pressure P_L decrease. At point *D*, the turgor pressure reaches the critical level and stomata begin to close.

(4) At very high transpiration demands, above point *D*, there is no shoot growth. Stomatal closure means that the plant can meet only a fraction of the transpiration demand and the actual transpiration rate falls below potential rate

The following relationships and hypotheses are incorporated into the model. All values below are defined for soil cells (elements) and are assumed to be constant within the cells. Physical units are g, cm, day, °C, and bars for pressures and potentials.

1. Water uptake and root growth take place preferentially in the soil cells where soil conditions are most favorable for growth. Root growth depends on the following soil state variables: soil water potential ψ_s , soil temperature T_s , and soil oxygen content g_{Ox} . A root growth reduction factor f_{rg} is calculated for every element as: $f_{rg} = \min(f_{rg,1}(\psi_s), f_{rg,2}(T_s), f_{rg,3}(g_{Ox}))$. The reduction factor components $f_{rg,1}(\psi_s)$, $f_{rg,2}(T_s)$, and $f_{rg,3}(g_{Ox})$ account for the effects of soil moisture, soil temperature, and soil redox status. A root growth reduction factor is calculated for each variable. The value with the smallest magnitude is considered to be most limiting and that minimum value is used to reduce potential root growth. The soil cells are then renumbered in the order highest to lowest based on their values of f_{rg} . The cells nearer the plant stem base have priority in the list when any two cells have the same value of f_{rg} .

The reduction of root growth due to changes in soil water potential is based on the concept of root osmoregulation. Greacen and Oh (1972) showed that roots osmoregulate with 90% efficiency against soil water potential changes and with 70% efficiency against changes in soil mechanical resistance. It seems unlikely, however, that roots can make these adjustments as rapidly as soil water potential can change during the day. Therefore, it is assumed that root osmoregulation is complete at dawn but operates at half the dawn efficiency during the day. It is also assumed that the expanding cells in the root tip, being in intimate contact with the soil, will have a water potential equal to that of the soil. The root osmotic potential at dawn $\pi_{R,D}$ depends

on soil water potential at dawn $\psi_{s,D}$ and soil mechanical resistance pressure $P_{M,D}$: $\pi_{R,D} = 0.9\psi_{s,D} - 5.5 - 0.7P_{M,D}$. The root turgor pressure at dawn $P_{R,D}$, is equal to the difference between root water potential at dawn $\psi_{R,D}$ and root osmotic potential, i.e., $P_{R,D} = \psi_{R,D} - \pi_{R,D}$. Since root and soil water potentials are assumed to be equal, $P_{R,D} = 0.1\psi_{s,D} + 5.5 + 0.7P_{M,D}$. Subtracting the threshold turgor pressure at which root growth starts, $P_{R,T}$ (= 3.5 bars), we obtain $P_{R,D} = 0.1\psi_{s,D} + 2.0 + 0.7P_{M,D}$. The turgor pressure available to expand the root after overcoming soil mechanical resistance at dawn is: $\Delta P_{R,D} = P_{R,D} - P_{M,D}$. At any other time of day a similar relationship is used with appropriate values of the variables: $\Delta P_R = P_R - P_M$. The threshold pressure for root growth to occur is 3.5 bars, and the maximum value that ΔP_M can attain is 5.5 bars. Assuming root growth is proportional to ΔP_M over this range, the proportion of maximum root growth possible at the given soil water potential and soil mechanical resistance pressure is:

$$r_{gl,1}(\psi) = (\Delta P_{M,D} - P_{R,T}) / (5.5 - P_{R,T}) = (P_R - \mu_R - 3.5) / 2$$

If the root osmoregulates with half efficiency during the day then, the change in root turgor pressure will equal half any change in root water potential. That is, $P_R = P_{R,D} - (\psi_{R,D} - \psi_R) / 2$, where ψ_R is root water potential during the day. Recalling that $\psi_R = \psi_s$ and substituting in the earlier equation, we have finally:

$$r_{gl,1}(\psi) = (P_{R,D} - P_M) / 2 - (\psi_{R,D} - \psi_{s,D}) / 4$$

The soil mechanical resistance, μ_R , depends on the soil bulk density ρ_s and soil moisture content θ as:

$$\mu_R = 0.5 + 100 * (0.14 - \theta) \exp[-8.08(1.66 - \rho_s)]$$

Root growth reduction due to changes of temperature is modeled using the data of White (1937), and root response to oxygen concentration is based on the data of Eavis et al. (1971):

$$f_{rg,2}(T) = (T/30)^b, \quad b = \begin{cases} 3.66, & T < 30^\circ \\ -15.4, & T \geq 30^\circ \end{cases}$$

$$f_{rg,3}(g_{Ox}) = \begin{cases} 0.15 + 4000g_{Ox}, & g_{Ox} \leq 2.13 \cdot 10^{-4} \\ 1.00, & g_{Ox} > 2.13 \cdot 10^{-4} \end{cases} \quad (10.1)$$

2. The threshold turgor pressure required for shoot cell growth adjusts dynamically. It has been shown that a decrease in turgor pressure is followed by a decrease in the threshold turgor pressure required for cell growth. Thus, growth over a period, Δt , is only decreased if the turgor pressure falls more than the threshold turgor pressure can adjust in that time. The rate of threshold adjustment is higher at high turgor pressure. This relationship is expressed in the form:

$$\frac{P_{LT}^{-2}}{\max(P_L^0, P_{LT}^0) - 2} = \exp(-16.8\Delta t) \quad (10.2)$$

Here P_{LT} is the threshold leaf turgor pressure at the end of the Δt interval; P_{LT}^0 is the threshold leaf turgor pressure at the beginning of the Δt interval; and P_L^0 is leaf turgor pressure at the beginning of the Δt interval. This dependence is based on the data of Green et al. (1971).

3. There is a dynamic relationship between leaf water potential and leaf turgor pressure that is controlled by osmoregulation. Any change in leaf water potential during the day is partially balanced by a change in leaf osmotic potential. Measurements for soybean and cotton have shown changes in leaf osmotic potential to be equal to half the changes in leaf water potential. This appears to be one way plants become conditioned to water stress. In the model, temporal increments of leaf water potential and turgor pressure are proportional:

$$1 - f_\pi = \frac{\psi_L - \psi_L^0}{P_L - P_L^0} \quad (10.3)$$

Here, and subsequently, ψ_L is leaf water potential and P_L is leaf turgor pressure. The superscript 0 indicates the beginning of the time interval, and the absence of the superscript indicates the end of this interval. The parameter f_π is the factor in the model that simulates conditioning to water stress. The osmoregulation concept allows us to not only calculate changes in the leaf turgor pressure but also to calculate critical levels of the leaf water potential from known critical or threshold values of the turgor pressure. The threshold value of the leaf water potential ψ_{LT} that prevents all shoot expansion is:

$$\psi_{LT} = \max(\psi_L^0, \psi_{LT}^0) + \frac{P_{LT} - \max(P_L^0, P_{LT}^0)}{1 - f_\pi} \quad (10.4)$$

The leaf water potential at 2 bars of turgor pressure $\psi_{L,2}$ is:

$$\psi_{L,2} = \psi_L^0 - \frac{2 - P_L^0}{1 - f_\pi} \quad (10.5)$$

The leaf water potential at zero turgor $\psi_{L,0}$ is:

$$\psi_{L,0} = \psi_L^0 - \frac{P_L^0}{1 - f_\pi} \quad (10.6)$$

4. Water uptake for existing and new roots is a function of root length and the difference between soil and leaf water potentials. In each soil cell there are mature roots (older than two days), young roots, and new young roots. The new young roots appear during the current Δt interval. The model uses auxiliary water uptake variables to determine how the potential transpiration rate relates to various potential water uptake rates. These values correspond to points Z and C-Z on Fig. 10.1 and they are calculated as:

$$u_i^0 = \left(\frac{L_M A_s}{r_M} + \frac{l_Y}{r_{Y_i}} \right) (\psi_s - \psi_{LT})_i$$

$$\Delta u_i = \left(\frac{\Delta l_Y}{r_{Y_i}} \right) (\psi_s - \psi_{LT})_i \quad (10.7)$$

where

u_i^0 - water uptake by existing roots from soil cell i , g-plant⁻¹·day⁻¹, when the leaf water potential equals the threshold value that prevents all shoot expansion. It corresponds to point Z in Fig. 10.1. This is the additional water uptake from roots grown with the extra carbon diverted from canopy growth.

Δu_i - additional water uptake by new roots from soil cell i , $\text{g} \cdot \text{plant}^{-1} \cdot \text{day}^{-1}$, when all additional carbon is made available for root growth and the leaf water potential is less than the threshold value that prevents all shoot expansion, point C-Z in Fig. 10.1.

I - order of favorability for root growth ($i=1$ is the most favorable),

L_M - density of mature roots in the soil cell, g cm^{-2} ,

A_s - area of the soil cell, cm^2 ,

l_Y - length of young roots in the soil cell from the previous time steps, cm,

Δl_Y - length of young roots that appear in the soil cell during the current time interval, cm,

r_M - total resistance of the water path from soil to leaf through mature roots, $\text{bar} \cdot \text{day} \cdot \text{g}^{-1} \cdot (\text{cm of root})$,

r_Y - same as above for the young roots, $\text{bar} \cdot \text{day} \cdot \text{g}^{-1} \cdot (\text{cm of root})$.

r_V - root vascular resistance, $\text{bar} \cdot \text{day} \cdot \text{g}^{-1} (\text{cm root})$.

RVRL Radial vascular root resistance per cm root $\text{bar} \cdot \text{day} \cdot \text{g}^{-1} \cdot (\text{cm of root})$.

Resistances to flow of water in the plant-soil system include soil resistances, r_s , root radial resistances, r_{RM} and r_{RY} , and root vascular resistance r_V . All are altered by water viscosity which is given as a function of temperature by Dalton and Gardner (1978) as:

$$r_V = (RVRL) \frac{\sqrt{(x^2 + y^2)}}{4}$$

$$r_Y = (r_s + r_{RY} + r_V) / 0.002275 / (T + 24.5)$$

$$r_M = (r_s + r_{RM} + r_V) / 0.002275 / (T + 24.5)$$
(10.8)

Here x and y are the distances from the center of the cell to the stem of the plant. The radius of the soil cylinder through which water must travel to reach the root is normally considered to be a function of root density. However, it is actually a function of soil water content, soil hydraulic properties, and root water uptake rate. In this model, to avoid interactions, the radius of the soil cylinder is made a simple function of soil water potential: $d_{sc} = 0.017 - 0.05 \psi_s$. The equation is based on the data of Cowan (1965). Resistance to water flow in the soil, r_s , is calculated by assuming steady-state diffusion of water across the soil cylinder to the root surface (Gardner,

1960). The average root radius is assumed to be 0.017 cm (Taylor and Klepper, 1975), and $r_s = \ln(d_{sc}^2 / (3 \cdot 10^{-4})) / (4 \pi K \cdot 1019)$, where K is an average soil hydraulic conductivity in the cell.

The values for vascular resistances were calculated from data of Bunce (1978). The overall plant resistance was partitioned between leaf, vascular, and root radial resistances in the proportions reported by Boyer (1971). Since the roots in both the Bunce and Boyer data were probably not growing very rapidly (transpiration demand was low), the root radial resistance obtained by this method was assumed to be the one for "old" roots. "Young" roots have a lower resistance than "old" ones (Russel, 1977). The ratio of "old" to "young" resistances found by Brouwer (1965) was used to estimate a radial resistance for "young" soybean roots. In this model the roots remain "young" for two days after they are grown.

5. The amount of new root growth and water uptake during the current time interval depend on the amount of carbon translocated from the shoot. The rate of carbon translocation B_R to roots varies between $B_{R,min}$ and $B_{R,max}$. The former occurs if roots get only the carbon left over after above ground growth is satisfied; the latter represents the case when roots get all the carbon translocated from the leaves. Therefore, the ratio $\xi = (B_R - B_{R,min}) / (B_{R,max} - B_{R,min})$ may vary between 0 and 1.

If the ratio ξ is zero, i.e. $B_R = B_{R,min}$, then the total water uptake by old and new roots U_l , corresponding to point Z in Fig. 10.1 is equal to

$$U_l = \sum_{i=1}^{i=N_e} u_i^0 + \sum_{i=1}^{i=i_l} \Delta u_i \kappa_i \quad (10.9)$$

Here water uptake by old roots is summed for all soil cells (N_e) and water uptake by young roots is summed over those soil cells where new roots grow. These soil cells have numbers from 1 to i_l . Weighting factors κ_i are equal to 1 in all cells because roots grow at the potential rate except where cell # = i_l . In the last cell, i_l , the value of κ_i may be less than 1 because there may not be enough carbon to meet the potential growth rate. The weighting factors κ_i for this cell satisfy the following equations:

$$\begin{aligned}
\sum_{i=1}^{i=i_1} (\Delta l_Y)_i \kappa_i &= B_{R,\min} / (b_R W_R), \\
\kappa_i &= 1, \quad i=1, 2, \dots, i_1-1, \\
\kappa_{i_1} &= \frac{B_{R,\min} / (b_R W_R) - \sum_{i=1}^{i=i_1-1} (\Delta l_Y)_i}{(\Delta l_Y)_{i_1}}, \\
\kappa_i &= 0, \quad i > i_1
\end{aligned}
\tag{10.10}$$

Here b_R is amount of carbon needed to make unit root dry mass, $\text{g} \cdot \text{g}^{-1}$, and W_R is the average root dry weight per unit length, $\text{g} \cdot \text{cm}^{-1}$.

If the ratio ξ is 1, the total water uptake by old and new roots U_2 corresponding to point C in Fig 10.1 is equal to:

$$U_2 = \sum_{i=1}^{i=N_e} u_i^0 + \sum_{i=1}^{i=i_2} \Delta u_i / \kappa_i
\tag{10.11}$$

Here $u_i^0 > u_i$ and represents uptake by the roots grown with additional carbon. The difference between U_1 and U_2 lies in the number of cells with young roots. This number i_2 for U_2 and corresponding weighting factors, κ_i , satisfy the following equations:

$$\begin{aligned}
\sum_{i=1}^{i=i_2} (\Delta l_Y)_i \kappa_i &= B_{R,\max} / (b_R W_R), \\
\kappa_i &= 1, \quad i=1, 2, \dots, i_2 - 1, \\
\kappa_{i_2} &= \frac{B_{R,\max} / (b_R W_R) - \sum_{i=1}^{i=i_2-1} (\Delta l_Y)_i}{(\Delta l_Y)_{i_2}}, \\
\kappa_i &= 0, \quad i > i_2
\end{aligned}
\tag{10.12}$$

6. Low potential transpiration rates can be met from water uptake by old roots and new ones growing with the minimum carbon supply rate B_{\min} . In this case the leaf water potential at the beginning of the current time interval corresponds to point B in Fig. 10.1 and the water uptake rate U_B is equal to

$$U_B = U_1 \frac{\psi_L^0 - \psi_s^a}{\psi_{LT} - \psi_s^a}
\tag{10.13}$$

Here ψ_s^a is the average soil water potential in the cells where new roots extract water. If the transpiration demand, E , is less than U_B , then the leaf water potential at the end of the current time interval, ψ_s , will be larger than at the beginning, ψ_s^0 and is calculated as:

$$\psi_L = \psi_s^a + \frac{E}{U_B} (\psi_L^0 - \psi_s^a)
\tag{10.14}$$

The root carbon supply ratio ξ is equal to zero and the shoot has no growth limitation.

7. Intermediate potential transpiration rates reduce shoot growth by some fraction. At these transpiration rates the demand for water uptake cannot be met without shoot water potential falling to the point where the shoot loses turgor and stops growing for part of the time interval. When this happens, additional carbon is sent to the roots to increase root growth. The potential transpiration rate ranges between U_B and U_2 . The carbon supply ratio $\xi = (\psi^0 L - \psi_L) / (\psi^0 L - \psi_{LT})$, and leaf water potential has a non-linear dependence on transpiration rate:

$$E_C = \frac{\psi_s^a - \psi_L}{\psi_s^a - \psi_{LT}} [U_1 + (U_2 - U_1) \frac{\psi_L^0 - \psi_L}{\psi_L^0 - \psi_{LT}}] \quad (10.15)$$

8. High potential transpiration rates can be met from water uptake by mature roots and new roots growing with the maximum carbon supply $B_{R,max}$. The potential transpiration rate at point C in Fig. 10.1 corresponds to the minimum transpiration demand that completely prevents shoot growth. If transpiration demand is higher than U_2 , then leaf water potential exceeds its threshold value. Leaf water potential is calculated as:

$$\psi_L = \psi_s^a + \frac{E_C}{U_2} (\psi_{LT} - \psi_s^a) \quad (10.16)$$

The root carbon supply ratio ξ is equal to one and the shoot does not grow as all available carbon is translocated to the roots. Very high transpiration demands can result in leaf turgor pressures less than 2 bars and leaf water potentials less than $\psi_{L,2}$. In this case, stomatal closure occurs and the transpiration rate decreases. The leaf water potential is now calculated as:

$$\psi_L = \frac{\psi_s^a + \frac{E_C(\psi_s^a - \psi_{L,2})}{U_2(\psi_{L,2} - \psi_{L,0})} \psi_{L,0}}{1 + \frac{E_C(\psi_s^a - \psi_{L,2})}{U_2(\psi_{L,2} - \psi_{L,0})}} \quad (10.17)$$

The reduction of transpiration rate is found by multiplying the potential transpiration rate, E , by the ratio $(\psi_L - \psi_{L,0})/(\psi_{L,2} - \psi_{L,0})$.

9. At the beginning of the day, leaf water potential is fixed at the dawn value. At dawn, the leaf water potential is set to the soil water potential.

10. The stomata close overnight and under water stress. It is assumed that the fluxes of carbon dioxide and water are reduced to 10% of the maximum rate when the stomata close at night and the plants have not experienced water stress. The value of 10% is derived from the data of Boyer (1970). If the plants have experienced stress, the stomata are assumed to close to the point where fluxes are reduced to 1% of the maximum rate. If stomata close at any time during the day, leaf osmoregulation occurs.

11. The turgor pressure itself may influence carbon partitioning between shoot and root. If turgor pressure is less than 5 bars and decreasing, shoot growth potential is partially reduced by sending some additional carbon to the roots. The carbon supply ratio is altered and the value of $1 - (1 - \xi)(P_L - 2)/3$ is used instead of ξ .

12. Water uptake from each soil cell depends on the leaf water potential, root carbon partitioning ratio, and the potential for new root growth. Initially the approximate water uptake of mature and young roots corresponding to available carbon and leaf water potential is found for every cell:

$$\tilde{u}_i = (u_i^0 + \Delta u_i \kappa_i) \left(\frac{\psi_s - \psi_L}{\psi_s - \psi_{LT_i}} \right), \quad i = 1, 2, \dots, N_e \quad (10.18)$$

Here, the weights κ_i correspond to the amount of carbon available for root growth as:

$$\begin{aligned}
\sum_{i=1}^{i=i_\xi} (\Delta l_\gamma)_i \kappa_i &= (B_{R,\min} + \xi B_{R,\max}) / (b_R W_R), \\
\kappa_i &= 1, \quad i=1, 2, \dots, i_\xi - 1, \\
\kappa_{i_\xi} &= \frac{(B_{\min} + \xi B_{\max}) / (b_R W_R) - \sum_{i=1}^{i=i_\xi-1} (\Delta l_\gamma)_i}{(\Delta l_\gamma)_{i_\xi}}, \\
\kappa_i &= 0, \quad i=i_\xi+1, i_\xi+2, \dots, N_e.
\end{aligned} \tag{10.19}$$

The final values of water uptake from soil cells precisely correspond to the transpiration rate:

$$u_i = \tilde{u}_i \kappa_i \tag{10.20}$$

where the weight coefficients κ_i provide for the equality between the sum of \tilde{u}_i and E_C :

$$\begin{aligned}
E_C &= \sum_{i=1}^{i=i_E} \tilde{u}_i \kappa_i, \\
\kappa_i &= 1, \quad i=1, 2, \dots, i_E - 1, \\
\kappa_{i_E} &= \frac{E_C - \sum_{i=1}^{i=i_E-1} \tilde{u}_i}{\tilde{u}_{i_E}}, \\
\kappa_i &= 0, \quad i=i_E+1, i_E+2, \dots, N_e.
\end{aligned} \tag{10.21}$$

13. Roots can grow into adjacent soil cells after their density in any one cell exceeds a threshold value. Root growth occurs in the most favorable cells, and the total increment of new root mass is equal to $(B_{R,\min} + \xi B_{R,\max}) \Delta t / b_R$. Any increase in root mass in a cell that has a root mass

above the threshold value, $\rho_{R,T}A_{ss}$, is distributed between that cell and its neighbors in proportion to the favorability for root growth in the new cells. The cells below the cell in question and on the side furthest from the plant have weights that determine whether the majority of root mass is distributed laterally or vertically. Potential root growth is proportional to the mass of existing roots in the given cell I : $(\Delta m_R)_I = \alpha_M(m_R)_i \Delta t$. The length of young roots in each cell decreases as they mature, and new roots may be added at the same time as new growth. New (young) root length is calculated as:

$$(\Delta l_Y)_I = -\alpha_Y(l_Y)_i \Delta t + (\Delta m_R)_I / W_R.$$

The decrease in length of young roots is reflected in the increase in length of mature roots:

$$(\Delta l_M)_I = \alpha_Y(l_Y)_i \Delta t / (A_s)_I.$$

10.1.1 Data files '*Param_R.dat*' and '*Nodal_R.dat*'

The parameters for this water uptake and root growth module are in the data file '**Param_R.Dat**' and the description of the variables and file structure are in Table 10.1. The example listing of a file is in Example 10.1 that contains parameters for a soybean plant. For every soil cell, the initial root mass distribution and the numbers of neighboring soil cells are given in the file '**Nodal_R.dat**'. The example listing in Example 10.2 corresponds to the grid in Fig. 3.1.

Table 10.1. Format of the file 'Param_R.dat'.

Record	Variable	Description
1,2	-	Comment lines.
3	<i>RRRM</i>	Radial resistance of old roots R_{RM} in soil cell, bar·day·(cm root)·g ⁻¹ .
3	<i>RRRY</i>	Radial resistance of young roots R_{RM} in soil cell, bar·day·(cm root)·g ⁻¹ .
3	<i>RVRL</i>	Root vascular resistance R_V per g of root between base of stem and soil cell, bar·day·(cm root)·g ⁻¹ .
4	-	Comment line.
5	<i>ALPM</i>	Potential relative old root growth rate α_M , day ⁻¹ .
5	<i>ALPY</i>	Potential relative young root elongation rate α_Y , day ⁻¹ .
5	<i>RTWL</i>	Average root dry weight per unit length W_R , g·cm ⁻¹ .
5	<i>RtMinWtPerUnitArea</i>	Threshold dry root mass ρ_{RT} that must be present in a unit volume of soil cell before roots can grow into adjacent cells, g·cm ⁻³ .
6	-	Comment line.
7	<i>Wl</i>	Weighting factor for the <u>left</u> adjacent cell to find the proportion of new roots proliferating to cell from given one.
7	<i>Wa</i>	Same as above for the <u>upper</u> adjacent cell.
7	<i>Wr</i>	Same as above for the <u>right</u> adjacent cell.
7	<i>Wl</i>	Same as above for the <u>lower</u> adjacent cell.
8	-	Comment line.
9	<i>BlkDn(1)</i>	Bulk density in the first soil layer, g cm ⁻³ .
9	<i>BlkDn(2)</i>	Same as above in the second layer.
9	<i>BlkDn(NMat)</i>	Same as above in the last layer.
10		Comment line

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**** Example 10.1: WATER_UPTAKE01 PARAMETERS: FILE 'PARAM_R.DAT'
RRRM  RRRY  RVRL
167      313      7.3
ALPM      ALPY      RTWL      RtMinWtPerUnitArea
0.5      0.5      9.0E-05      9.0E-06
Wl      Wa      Wr      Wb
1.0      1.0      1.5      5.0
BlkDn(1)  BlkDn(2)  .....  BlkDn(Nmat)
1.4      1.35
END OF FILE 'PARAM_R.DAT'

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Table 10.2. Grid information for Water_Uptake01 module (file 'Nodal_R.dat').

Record	Variable	Description
1,2	-	Comment lines.
3	<i>e</i>	Number of soil cell (element)
3	<i>RTWT(e)</i>	Initial dry weight of roots in the soil cell <i>e</i> , g.
3	<i>iLeft</i>	Number of the left adjacent soil cell
3	<i>iUpper</i>	Number of the upper adjacent soil cell
3	<i>iRight</i>	Number of the right adjacent soil cell
3	<i>iLower</i>	Number of the lower adjacent soil cell


```

**** Example 10.2: WATER_UPTAKE01 GRID DATA: FILE 'NODAL_R.DAT'
e      RTWT      iLeft iUpper iRight iLower
1       0         1      1       2       3
2       0         1      2       2       4
3      0.004       3      1       4       6
4       0         3      2       5       7
5       0         4      5       5       8
6       0         6      3       7       9
7       0         6      4       8      10
8       0         7      5       8      11
9       0         9      6      10       9
10      0         9      7      11      10
11      0        10      8      11      11
END OF FILE 'NODAL_R.DAT'

```

10.2 Plant status independent model: Water_Uptake02

This model of root activity is essentially the same as that introduced by Feddes et al. (1978) with amendments from others (Wesseling and Brandyk, 1985; Vogel, 1987; Van Genuchten et al., 1992). This model does not take into account dynamic plant development and root growth in response to water deficits. This and similar models have been successfully used for grass canopies (Pachepsky and Zborishchuk, 1984). For a given soil cell, (element), the water uptake rate S , day^{-1} , is equal to

$$S(h,x,z) = f_{str}(h) b_R(x,z) \frac{d_{Tr} E_c}{A} \quad (10.22)$$

where E_c is potential transpiration, cm day^{-1} ; d_{Tr} is the width of soil surface associated with transpiration, cm ; $b_R(x,z)$ is proportion of root mass in the soil cell at the elevation coordinate z , and lateral coordinate x ; A is the area of the soil cell, cm^2 ; h is pressure head in the soil cell; and f_{str} is the water stress response function shown in Fig. 10.2. The water stress response function, f_{str} , depends on four parameters: h_0 , h_1 , h_2 , and h_3 . The parameters h_0 and h_3 are assumed constant, h_1 depends on soil properties, and h_2 depends on transpiration rate as:

$$h_2 = h_{2,high} + (h_{2,low} - h_{2,high}) \frac{E_{c,high} - E_c}{E_{c,high} - E_{c,low}}, \quad E_{c,low} < E_c < E_{c,high}$$

$$h_2 = h_{2,high}, \quad E_c \geq E_{c,high}$$

$$h_2 = h_{2,low}, \quad E_c \leq E_{c,low}$$

(10.23)

where $E_{c,low}$, $E_{c,high}$, $h_{2,low}$, $h_{2,high}$ are plant dependent parameters.

To estimate the order of magnitude and range of parameters, one may consider $h_3 = -8000$ cm,

$E_{c,low} = 0.1$ cm/day, $E_{c,high} = 0.5$ cm/day,

$h_{2,low} = -800$ cm, $h_{2,high} = -200$ cm, $h_1 = -$

25 cm, and $h_0 = -10$ cm.

10.2.1 Data files '*Param_U.dat*' and '*Nodal_U.dat*'

The structures of the data files '*Param_U.dat*' and '*Nodal_U.dat*' are shown in Tables 10.3 and 10.4. Listings of example files are in Examples 10.3 and 10.4.

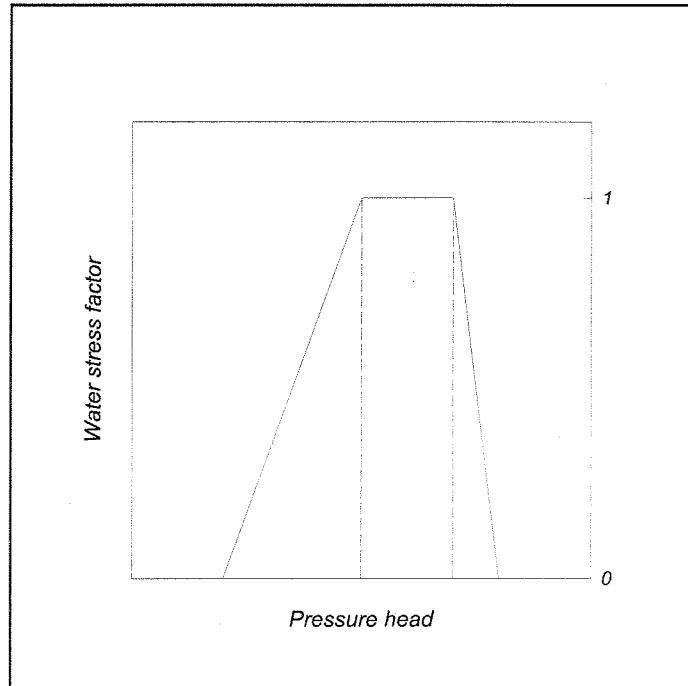


Figure 10.2 Water stress response function as used by Feddes et al., 1978, and Šimůnek et al., 1992.

Table 10.3. Format of the file 'Param_U.dat'.

Record	Variable	Description
1,2	-	Comment lines.
3	$P0$	Value of pressure head h_0 below which roots start to extract water from the soil, cm
3	$P2H$	Value of the limiting pressure head $h_{2,high}$, cm, below which the roots cannot extract water at the maximum rate (assuming a potential transpiration rate of $E_{c,high}$).
3	$P2L$	Value of the limiting pressure head $h_{2,low}$, cm, above which the roots can extract water only at the minimum rate (assuming a potential transpiration rate of $E_{c,low}$).
3	$P3$	Value of the pressure head h_3 , cm, below which root water uptake ceases (usually wilting point).
3	$r2H$	Critical potential transpiration rate $E_{c,high}$, cm day ⁻¹ .
3	$r2L$	Critical potential transpiration rate $E_{c,low}$, cm day ⁻¹ .
4,5	-	Comment line.
6	$Poptm(1)$	Value of pressure head h_1 , cm, below which roots start to extract water at a maximum possible rate in soil material number 1.
6	$Poptm(2)$	As above for soil material # 2.
.	.	.
6	$Poptm(NMat)$	As above for soil material $NMat$

```

**** Example 10.3: WATER UPTAKE_02 PARAMETERS : FILE 'PARAM_U.DAT'
P0=h0 * P2H=h2,high * P2L=h2,low * P3=h3 * r2H=Ec,high * r2L=Ec,low
-10.      -200.      -800.      -8000.      0.5      0.1
Soil material data
Poptm(1)  Poptm(2)  .....  Poptm(NMat)
-25.      -40.0
END OF FILE 'PARAM_U.DAT'

```

Table 10.4. Format of the file 'Nodal_R.dat'.

Record	Variable	Description
1,2	-	Comment lines.
3	n	Element number.
3	$ROOTFR(n)$	Value of water uptake distribution $f_R(x,z)$ in soil root zone at element n . $ROOTFR(n)$ = zero if element n lies outside of the root zone.

Record 3 is supplied for each elements where roots are present.

```

**** Example 10.4: WATER UPTAKE_01 GRID DATA: FILE 'NODAL_R.DAT'
e      ROOTFR
2      0.27
3      0.73
END OF FILE 'NODAL_R.DAT'

```

10.3 A simple model of above ground plant growth, ShootImitator module

ShootImitator is a very simple model of shoot and leaf development used in 2DSOIL for two purposes: (1) to supply necessary soil-atmosphere boundary information, and (2) to provide dynamic evapotranspiration for root water uptake modules. This particular module is provided as a place holder for a more comprehensive model of plant development when 2DSOIL is interfaced with a plant model. The module demonstrates what variables need to be shared, and allows 2DSOIL to be run before it is interfaced with a complete plant model.

The **ShootImitator** module uses a very simple model of CO₂ uptake as a function of light intensity. The model is taken from Acock et al. (1985) has the form of:

$$P_g = \frac{\alpha I \tau C}{\alpha I + \tau C}$$

Here P_g is gross photosynthetic rate (mg CO₂ m⁻² s⁻¹), C is carbon dioxide concentration (350 L L⁻¹), α , and τ are constants ($\alpha = 3.25 \mu\text{g CO}_2 \mu\text{mol}^{-1}$ photons, and $\tau = 5.69 \text{mm s}^{-1}$). It is assumed that 60% of the carbon actually becomes plant matter. A light partitioning coefficient is used to adjust for the amount of photosynthetically active light intercepted by the canopy. The time-dependent variables are calculated according as:

$$\begin{aligned}
\frac{dH_c}{dt} &= \begin{cases} 0.71 \frac{B_V}{B_{V,\max}} & t_{gr} < 75 \\ 0.1 \frac{B_V}{B_{V,\max}} & t_{gr} > 75 \end{cases} \\
\frac{dA_L}{dt} &= \begin{cases} 0.08 H_c & t_{gr} < 75 \\ 0.01 H_c & t_{gr} > 75 \end{cases} \\
\frac{B_V}{B_{V,\max}} &= \begin{cases} 1, & \psi_s^a > -1 \\ \frac{8 + \psi_s^a}{7}, & -8 < \psi_s^a \leq -1 \\ 0, & \psi_s^a \leq -8 \end{cases} \quad f_{CPR} = \begin{cases} 0.85 - 0.01 t_{gr}, & t_{gr} \leq 60 \\ 0.2, & t_{gr} > 60 \end{cases} \\
B_{R,\max} &= 0.95 B_{Vp} N_p, \quad B_{R,\min} = f_{CPR} B_{Vp} N_p, \quad b_R = 0.65 N_{SD} + 0.48 (1 - N_{SD}) \\
N_{fract} &= \begin{cases} 0.05 - 0.000533 t_{gr} & t_{gr} \leq 75 \\ 0.01 & t_{gr} > 75 \end{cases} \\
N_{SD} &= \frac{N_{upt}}{N_{fract} \times B_V \times 1.67}
\end{aligned}$$

(10.25)

Here, H_c is plant height (cm), A_L is total plant leaf area (cm²), $B_{R,\min}$ is the rate of carbon supply to roots after satisfying shoot demand (g plant⁻¹ per half soil slab), $B_{R,\max}$ is the rate of carbon supply to roots when shoot growth ceases, b_R is mass of carbon per unit of root dry mass, t_{gr} is time counted after emergence, Ψ_s^a is average soil potential in root-inhabited soil cells, bars; f_{CPR} is the proportion of carbon supply partitioned to root; N_p is the number of plants per meter of row; N_{SD} is the nitrogen supply/demand ratio of the plant (set equal to 1 if there is no nitrogen

module), and N_{frac} is the fraction of N in plant tissues. We assume that 60% of the total plant tissue is carbon. Carbon for root growth is partitioned as a function of time after emergence. Initially 85% of the carbon fixed goes to the roots. This amount decreases by 1% each 24 hour period until it reaches a minimum of 2%. The plant is also sensitive to nitrogen deficiency. The nitrogen demand is high early in the season and falls as the plant reaches maturity. The initial nitrogen demand assumes the plant must maintain a nitrogen concentration of 5%. This will decrease linearly to 1% as the plant reaches maturity ($t_{\text{gr}}=75$). A weighting factor (N_{SD}) based on the ratio of actual N uptake to desired N uptake is calculated and used to adjust the shoot growth rate. The ratio is based on cumulative nitrogen uptake to allow the plant to store excess N.

Both soil-root surfaces and soil atmosphere surfaces are controlled by several plant status variables that are listed in Table 10.5. These are public variables in the plant block. These variables are defined by the **ShootImitator** and used by the **SetSurf** and **WaterUptake** modules. The public variables that are supplied by **ShootImitator** include the time-dependent values of H_c , A_L , $B_{R,\text{min}}$, $B_{R,\text{max}}$, and b_R . **ShootImitator** also supplies some constant parameters such as geometrical parameters of the canopy that include: position of the stem base, row spacing, number of plants per 1 meter of a row, row orientation, and the canopy extinction coefficient.

Table 10.5. Public information that interfaces the ShootImitator (SI) module with the SetSurf02 (SS2), SetSurf01 (SS1), and WatUp01 (WU1) modules.

Variable	Meaning	Usage			
		SI	SS2	SS1	WU1
ITIME	Number of the current hour counting from midnight		P		U
IDAWN	Hour number when dawn occurs		P		U
IDUSK	Hour number of dusk occurs		P		U
xBSTEM	Horizontal coordinate of the stem base, cm	P	U	U	U
yBSTEM	Vertical coordinate of the stem base, cm	P			U
CONVR	Amount of carbon needed to make unit dry weight of root, g g^{-1}	P			U

Variable	Meaning	Usage			
		SI	SS2	SS1	WU1
PCRL	rate at which carbon would be supplied to growing roots in a soil slab if all potential shoot growth had been satisfied, g per day per half soil slab	P			U
PCRQ	rate at which carbon would be supplied to growing roots in a soil slab if all translocated carbon went to roots, g per day per half soil slab	P			U
SGT	proportion of time for which shoot grows: limited by shoot turgor or carbon availability	U			P
PSIM	Average soil suction in soil cells with roots, bars	U			P
LAREAT	total leaf area per plant, cm ²	P	U		
HEIGHT	Height of the plant, cm	P	U	U	
POPROW	plant population per meter of row	P			U
ROWSP	Row spacing, cm	P	U		
ROWANG	row orientation measured eastward from North, degrees	P	U		
VEGSRC	net mean carbon production per plant per day (g).	P			
CEC	Canopy extinction coefficient				
Nitrogen_t	Cumulative nitrogen uptake, g per plant	U			P

* 'P' means that the value of a variable is produced by the module, 'U' means that the value of a variable is used by the module.

Table 10.6 Variables output by Shootliminator in the file 'Plant.out'

Variable	Description
Height	Plant Height, cm
Lareat	Total Leaf area per plant, cm ²
Total_eor	Total water use per plant, g
Total_pcrs	Total amount of carbon actually used to grow roots, g
Cover	Leaf cover, %
Carbon_t	Cumulative net carbon use in the above ground part of the plant, g
PCarbon_t	Potential carbon production per plant, g
UCarbon_t	Cumulative carbon production in entire plant, g

Nitrogen_t	Cumulative nitrogen uptake, g per plant
NDef	Ratio of nitrogen requirement to nitrogen taken up
Psim	Average matric potential in the elements with roots, bars
Sgt_m	Daily mean of SGT

10.3.1 The data file 'Param_p.dat'

The parameters needed by the **ShootImitator** are read from the data file '**Param_p.dat**'. The structure of the file is listed in Table 10.6 followed by a listing of a file as an example.

Table 10.6. Format of the file '**Param_p.dat**'.

Record	Variable	Description
1,2	-	Comment lines.
3	<i>POPROW</i>	Plant population per meter of row.
3	<i>ROWSP</i>	Row spacing, cm.
3	<i>ROWANG</i>	Row orientation measured eastward from north, degrees.
3	<i>xBSTEM</i>	Horizontal coordinate of the stem base, cm.
3	<i>yBSTEM</i>	Vertical coordinate of the stem base, cm.
3	<i>VEGSR</i>	net mean carbon production per plant per day (g). This variable is only used in Shootimitator3 which does not require values of radiation.
3	<i>CEC</i>	Canopy extinction coefficient.

*** Example 10.5: Shoot imitator data - file 'Param_p.dat'.

```
POPROW  ROWSP  ROWANG  xBSTEM  yBSTEM  VEGSRC  CEC
14      50     140     25      60.     2.14    0.55
END OF FILE 'PARAM_P.DAT'
```

10.4 Interfacing 2DSOIL with a crop model

This section is included to demonstrate how 2DSOIL can be interfaced with plant shoot models. To interface 2DSOIL with a crop model, the crop modeler needs to concentrate only on the boundary interface. The modeler must (a) assign potential boundary fluxes of water, solutes, heat and gases from their atmosphere module to the nodal boundary fluxes, (b) receive actual

boundary flux values from the water transport module and use them as needed, (c) pass potential transpiration and carbon flux values from the plant module to the root module, (d) receive actual transpiration, water and nutrient fluxes from the root module and use them as needed, and (e) provide simulated times when the plant and atmosphere modules will be ready to exchange information. All variables needed for this exchange are global public variables, and no code has to be changed in the other modules of the soil simulator. If some other soil variables are needed by the plant and atmosphere components, they are accessible through the global COMMON block since all global public data for the boundary interface are available there. If some private root variables are needed by the shoot module, they can be made accessible by inserting a local public COMMON block of the root module into the boundary interface. Finally, if the crop modeler wants to use their own root module, the module must be rearranged to fit into the data structure of the design described here.

