

MODELLING WATER AND NUTRIENT UPTAKE OF CROPS GROWN IN PROTECTED CULTIVATION

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Keywords: electrical conductivity, osmotic head, root, root length density, two-dimensional model

Abstract

This paper presents results of model calculations on uptake of water and nutrients by a lettuce crop grown in a sand bed. Emphasis is on the effect of salt concentration (osmotic head) on water uptake. This effect was studied using a two-dimensional model of water and nutrient transport in and uptake from a rooting medium. The main conclusion is that under normal conditions as found in Dutch horticulture, osmotic effect on water uptake is not important, but that it depends on the distribution of salts with respect to that of the roots.

1. Introduction

Crops grow only when water and nutrients are available for uptake by the root system. In protected glasshouse cultivation water and nutrients are supplied together as a nutrient solution (fertigation). Questions arise as to whether enough water and nutrients can be taken up so that optimal growth and quality can be guaranteed, while at the same time leaching can be minimized. To answer such questions it is important to know the spatial and temporal changes of the status of water and nutrients both in the plant and in the rooting medium, resulting from root uptake of water and nutrients. In this paper we present a simulation model for describing two-dimensional movement of water, nutrient transport and root uptake. It will be used to study the effect of (distribution of) salt concentration on water uptake.

2. Model description

2.1. Transport and uptake

Uptake of water and nutrients proceed according to different mechanisms. Water uptake is mainly a passive process. The evaporative power of the environment (governed by radiation, vapour pressure, wind speed, temperature) causes water to transpire from plant surfaces. Loss of water leads to a decreasing potential in the chain leaves, stems, roots and rhizosphere, resulting in flow of water to the roots, into the roots and eventually to the leaves. Van den Honert (1948) presented an attractive analog for this process consisting of series of resistances, where the flow is driven by and proportional to potential differences.

Nutrient uptake is mainly an active process, if necessary against a gradient in concentration; the plant has to spend energy in order to take up nutrients. Uptake rate by a root is usually described by uptake isotherms giving the uptake rate as a function of external concentration and some plant specific parameters. However, experiments haven shown that in case of the major nutrients the value of the concentration where uptake decreases is very low, e.g., less than 100 μM for nitrate (Heins and Schenk, 1986), and

about 1μM for P (Jungk, *et al.*, 1990). Moreover, there is usually considerable feedback between status (content) of a nutrient in plant tissue and realized uptake (Clarkson and Grignon, 1990). In other words uptake rate is to an important degree governed by plant demand, which in its turn depends on plant age, and meteorological conditions (radiation, temperature).

Based on the above mentioned results water and nutrient uptake in our models are both determined by plant demand. Limitations to meet the demand lie in the transport possibilities in the root medium, which depend on transport distances and parameters. The average (external) concentration and water content do play a role, but mainly (in our model: only) because the transport parameters and necessary gradient depend on these.

Nutrients and water are transported from bulk soil to rhizosphere by mass flow and diffusion. Mass flow occurs because, due to water uptake the water content (and thus the matrix pressure head) in the immediate vicinity of the root decreases which generates a gradient *in pressure head* leading to mass flow in the direction of the root. Diffusion is the transport along gradients of concentration, based on movement of fundamental particles like molecules and ions. Because the soil solution is very dilute, gradients in concentration of water are virtually zero, so this mechanism of transport for water is neglected in our model. For transport of solutes, however, diffusion is usually an important mechanism, the contribution of which to uptake often exceeds that of transport by mass flow.

2.1.1. Transport and uptake at the microscopic scale

The relevant transport equations can be solved analytically or numerically at the microscopic scale (De Willigen and Van Noordwijk, 1987, De Willigen and Van Noordwijk 1994 a,b), i.e. for a single root confined in a soil cylinder. With such equations the maximum transport rate of nutrients and water towards the root can be calculated. In order to do so the boundary condition at the root surface was that of constant (very low) concentration or water content.

2.1.2. Transport and uptake at a macroscopic scale.

The model which we used concerns a rectangular domain, representing a crosscut in depth perpendicular to the direction of plant rows. The physical dimensions of the rectangle can differ, but length and width are usually of the order of a few dm up to one meter. The rectangle is divided in compartments (CV control volumes). To use the solutions obtained for calculation in such a system of uptake, a root system with heterogeneous distribution of root length density would be unfeasible, unless one deals with a stationary root system regularly distributed in space. Fortunately, from the solutions pertaining to the micro scale macroscopic approximations could be derived, which can be used in case of heterogeneously distributed roots (De Willigen and Van Noordwijk, 1987, De Willigen, 1990). In such a macroscopic description the uptake terms do not appear as a boundary condition but as a sink term in the transport equation. In case of nutrients the maximum rate of uptake per unit root length S_{sm} (ML⁻¹T⁻¹) can be approximated by

$$S_{sm} = \pi L_{rv} D \frac{(\bar{c} - I)}{G(\rho, \nu)} \bar{c} \quad (1)$$

where \bar{c} is the average concentration of the nutrient (ML⁻³), L_{rv} the root length density (LL⁻³), D the diffusion coefficient of the soil (L²T⁻¹), ρ is the dimensionless radius of the soil cylinder, defined by $\rho = \left(R_0 \sqrt{\pi L_{rv}} \right)^{-1}$, R_0 being the radius of the root (L), ν is the dimensionless flux of water, and $G(\rho, \nu)$ a geometry function defined by:

$$G(\rho, \nu) = \frac{1}{2(\nu+1)} \left(\frac{1\rho^2}{2} + \frac{\rho^2(\rho^{2\nu}1)}{2\nu} + \frac{\rho^2(\rho^{2\nu}1)(\nu+1)}{2\nu(\rho^{2\nu+2}1)} + \frac{(1\rho^{2\nu+4})(\nu+1)}{(2\nu+4)(\rho^{2\nu+2}1)} \right). \quad (2)$$

The approximation is based on the assumption of a steady-rate distribution of the nutrient in the soil cylinder.

Likewise the rate of water transport q_2 (T^{-1}) towards a root with a given value of the pressure head at the root surface is approximated assuming a steady rate distribution of the matric flux potential in the soil

$$q_2 = \pi L_{rv} \frac{(\rho^2 - 1)}{G(0, \rho)} (\bar{\phi} - \phi_{rs}), \quad (3)$$

where $G(0, \rho)$ is a special case of the geometry function $G(\rho, \nu)$ given before, and the matric flux potential ϕ (L^2T^{-1}) is defined as

$$\phi = \int_{h_{ref}}^h K(h) dh, \quad (4)$$

where K is the hydraulic conductivity (LT^{-1}), h_{ref} is a reference value of the pressure head (L), and ϕ_{rs} and $\bar{\phi}$ correspond to the pressure at the root surface and in the bulk soil, respectively.

To explain the complete model in detail would consume too much space, an extensive description has appeared in Heinen and De Willigen (1992) and Heinen (1997). Here we will only pay attention to the formulation of the sink terms. It suffices to mention that the transport equation used in case of water is the celebrated Richard's equation, a combination of Darcy's law and the continuity equation. For nutrients it is the classical convection dispersion equation, describing transport by diffusion/dispersion and mass flow. Due to the strong non-linearity of the relation between water content and pressure head, and hydraulic conductivity and pressure head the equations have to be solved numerically.

2.2. Formulation of the sink terms for nutrients and water.

The uptake term for nutrients is based on the assumption that the root either takes up according to the demand of the crop, or to the maximum uptake rate allowed by soil properties and conditions. To calculate the required uptake rate the crop demand is divided by the total root length in the domain resulting in a required uptake per unit root length $S_{sr,c}$. Then, the uptake strength for a CV at position (I, J) is given by

$$S_{s,I,J} = \text{MIN} (S_{sr,c} L_{rv,I,J}, S_{sm,I,J}), \quad (5)$$

where the operator MIN yields the minimum value of its arguments. It is known that roots in favourable position can compensate for roots in less favourable position (e.g., De Jager, 1985, Clarkson and Grignon (1991)). So, if in some CV's nutrient uptake is limited by the maximum possible uptake, the solution procedure is iteratively continued for the remaining CV's to determine if they can compensate for roots in less favourable conditions.

The sink term for water uptake is somewhat more complicated, it is based on the assumption that the water flow from the bulk soil to the root surface, q_1 (T^{-1}), equals the

rate of flow over the root surface into the root driven by difference in pressure head h (L) and partly) by difference in osmotic head π (L)

$$q_l = L_{rv} K_l [h_{rs} - h_r + \sigma (\pi_{rs} - \pi_r)], \quad (6)$$

where K_l is the root conductance (LT^{-1}), h_{rs} is the pressure head (L) of the rhizosphere, h_r is the pressure head (L) in the root, σ is the reflection coefficient (-), π_{rs} the osmotic head (L) of the rhizosphere, and π_r the osmotic head (L) in the root. The sink strength S_w (T^{-1}), appearing in the Richards equation, for a CV at position (I,J) is then found by combining [3] and [6]

$$\begin{aligned} S_{w,I,J} &= L_{rv,I,J} K_l [h_{rs,I,J} - h_r + \sigma (\pi_{rs,I,J} - \pi_r)] = \\ &= \pi L_{rv,I,J} \frac{\rho_{I,J}^2 - I}{G(0, \rho_{I,J})} (\bar{\phi}_{I,J} - \phi_{rs,I,J}). \end{aligned} \quad (7)$$

The sum of all sink strengths then equals the actual transpiration rate T (LT^{-1})

$$T = \sum_{I=1}^N \sum_{J=1}^M S_{w,I,J} \quad (8)$$

T is a function of the root pressure head h_r and the potential transpiration rate T_p (LT^{-1}) according to (Campbell, 1985, 1991)

$$T = T_p \left(1 + \left(\frac{h_r}{h_{r,1/2}} \right)^a \right)^{-1}, \quad (9)$$

where $h_{r,1/2}$ is a species-dependent plant pressure head at which $T = 0.5T_p$ and a is a species-dependent dimensionless constant. The parameters K_l , h_r and R_0 are assumed to be constant for the whole root system, and h of the bulk soil in the CV is assumed to be known. This results in a set of $(N \times M + 1)$ equations with $(N \times M + 1)$ unknowns: $N \times M$ values of h_{rs} and h_r . However, due to the non-linear relationship between h and ϕ on the one hand and h_r and T on the other hand, the solution has to be found iteratively.

3. Parameters, functions, boundary and initial conditions

3.1. Dimensions of the domain and root distribution.

The majority of the necessary inputs was taken from an experiment as reported by Heinen (1997). This experiment was done in order to investigate the dynamics of water and nutrients in a sand bed, where lettuce was grown, which was fertigated frequently. The experimental setup is given in Figure 1, showing the position of the dripper and the drain and the dimensions of the bed. The root distribution is given in Figure 2, which is taken from Schwarz, *et al.* (1995). It pertains to the final root distribution of a mature lettuce crop (age 42 days) growing in a sand bed. Calculations were done for a 12 d period, during which root growth was described by a logistic function (Heinen, 1997).

3.2. Initial and boundary conditions.

The calculations pertained to a situation where the system was drying out for 12 days, without any application of water. Initially the pressure head distribution was in equilibrium with zero pressure at the bottom of the bed. The horizontal boundary conditions were that of zero flux, as was the bottom boundary condition. Over the top boundary evaporation took place.

3.3. Soil hydraulic properties

The calculations were done for three substrates, a coarse sand, a peat-perlite mixture and a rockwool. The experimental data of these substrates have been fitted to Mualem-Van Genuchten functions (Mualem, 1976, Van Genuchten, 1980) by Heinen (1997) for the coarse sand, Da Silva, *et al.* (1995) for the rockwool, and by Otten (1994) for the peat-perlite mixture. The value of the parameters can be found in Heinen (1997; his Table 8-2)

3.4. Nutrient supply.

From the nutrient concentrations the electric conductivity EC (dS m^{-1}) can be calculated according to the theory of ionic mobilities and ionic conductance (see any text book on physical chemistry; or, Heinen (1997), his Appendix 8). The osmotic head π_{rs} (cm) of the soil solution then can be computed as (US Salinity Laboratory Staff, 1954)

$$\pi_{rs} = -400 EC \quad (10)$$

The initial concentrations in substrate solution for N, K, P, Ca, Mg, Cl and Na were 21.0, 11.2, 4.0, 4.6, 1.0, 1.4, 0.5, 0.03 mmol l^{-1} . In one case the initial concentrations were twice these values.

3.5. Water uptake and transpiration

The root conductance was set at $3.6 \cdot 10^{-6} \text{ cm d}^{-1}$, an average value for different species, taken from De Willigen and Van Noordwijk (1987). The values of $h_{r,1/2}$ and a (Eq. [9]) were chosen such that reduction of transpiration begins when the root water pressure head h_r falls below -0.6 MPa , which was estimated by Heinen (1997) from data found in the literature.

The transpirational demand and the evaporation rate were set at values measured and calculated by Heinen (1997). When the osmotic head was taken into account the value of the reflection coefficient σ was set at 1, and the osmotic head within the root π_r at zero; this represents the worst case as far as hampering of water uptake by high concentrations is concerned.

4. Results and discussion.

The model has been validated by Heinen (1997) who showed that it was able to simulate satisfactorily experimental data. It was also used to do some explorative simulation studies. One of the important conclusions emanating from these studies was that the sand bed had to be irrigated frequently not because of lack of water per se, but to prevent the occurrence of spots with a too high concentration of solutes.

Here we will show some examples of the effect of osmotic head on water uptake by the plant and salt distribution in the substrates.

The first example deals with the effect of osmotic head on the root water pressure head. The effects of distribution of salt and roots in a soil profile were calculated. Both

salt and roots were assumed to have only gradients in the vertical direction. The root length density was supposed to decrease exponentially with depth. The salt was distributed in three ways: (I) constant with depth, (II) exponentially decreasing with depth, and (III) exponentially increasing with depth. The three distributions had the same average concentration. Figure 3A shows the salt distributions and Figure 3B the root water pressure head necessary for an uptake of 4 mm d^{-1} . Clearly, according to the calculations it is not so much the average concentration which has much significance, but the distribution of concentration with respect to that of the root distribution. With the parameter values used the most unfavourable distribution yielded a root pressure head of -3800 cm compared to -1000 cm for the most favourable distribution.

The next results apply to a period of 12 days of drying out. For the standard values of the parameters, inclusion of osmotic head did hardly affect the water uptake for all three root media. The potential transpiration was 20.8 ml , whereas the plant water uptake in case of the coarse sand, the rockwool and the peat-perlite mixtures amounted to 20.7 ml , 20.4 ml and 20.6 ml , respectively.

Figure 4 pertains to coarse sand only. Now the effect of halving the value of $h_{r,1/2}$ was investigated: it appears to be of limited influence only. Doubling the initial concentration, however, has a profound effect, reducing the total water uptake after 12 days to about 50% of the potential uptake.

Figure 5 and shows the distribution of the EC at the end of the 12 day period for $\sigma = 0$ and $\sigma = 1$, respectively, for the worst case situation. The distribution in case of $\sigma = 0$ (no effects of osmotic head; top diagram in Figure 5) is much more pronounced: the solutes accumulating in the upper 5 cm. In case of $\sigma = 1$ (bottom diagram in Figure 5) the increase in concentration at the substrate surface near the plant positions is much smaller. This difference is due to the distribution of the cumulative water uptake as given in Figure 6. In case of osmotic head effects the water has been taken up from deeper layers, in fact in the upper layers water has been transported from the roots into the soil, thereby diluting the soil solution. This outflow of water from the roots is a consequence of the way the water uptake is described, and could be an artefact. Outflow of water from roots, however, has been experimentally observed (e.g., Baker and Van Bavel, 1986).

The main conclusion (see Figure 3) from our calculations is that under normal conditions as found in Dutch horticulture, osmotic effects on water uptake are not important, but that this depends on the distribution of salts with respect to that of the roots.

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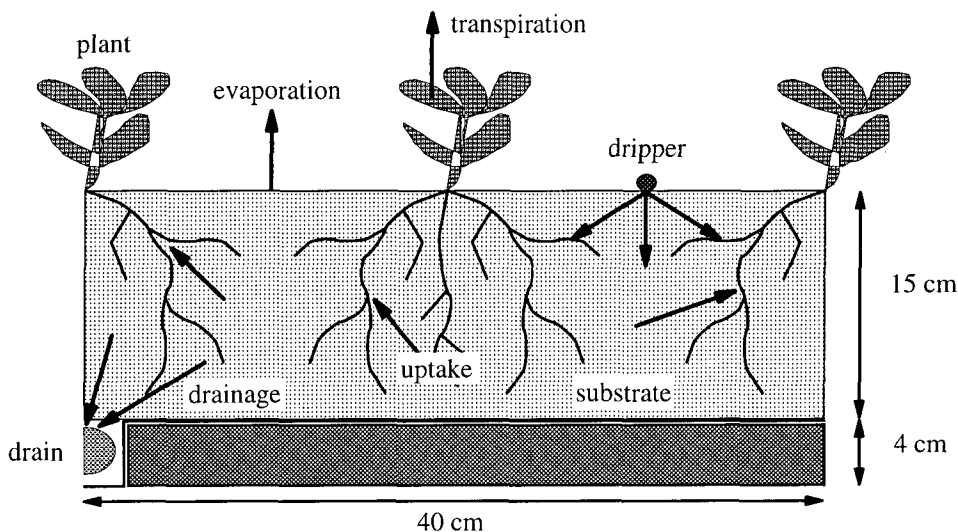


Figure 1: Schematic cross sectional view of the sand bed cropping system, indicating processes taken into account (adapted from Heinen, 1997).

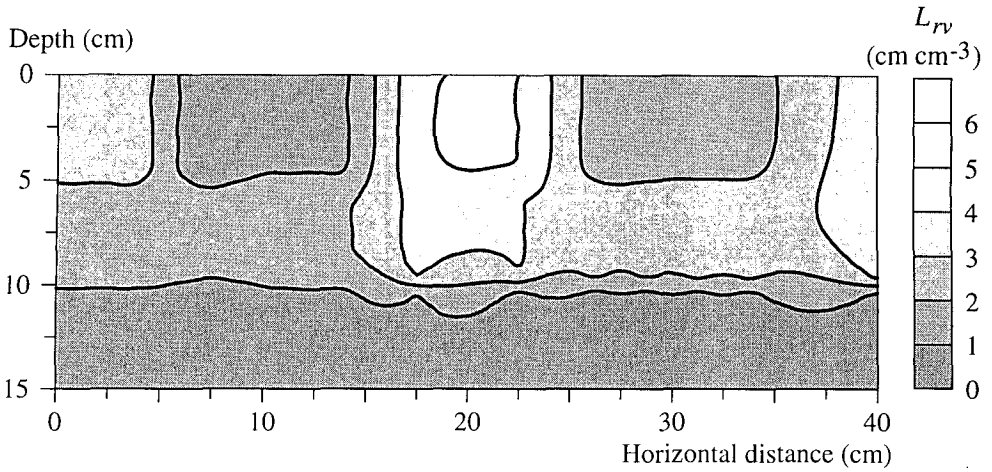


Figure 2: Final root length density, L_{rv} , distribution for a 42 days mature lettuce crop grown in a sand bed (refer to Figure 1; data from Schwarz *et al.*, 1995).

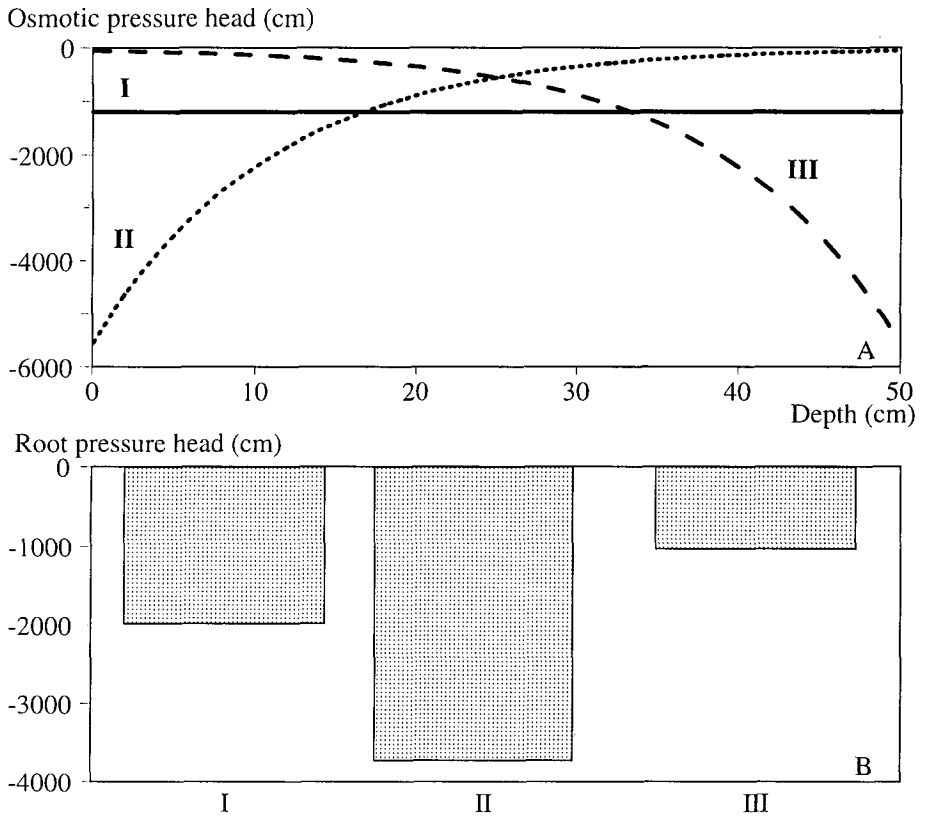


Figure 3: (A, Top) Initial salt distribution as a function of depth: I uniform distribution, II exponentially decreasing with depth, III exponentially increasing with depth, and (B, bottom) the resulting root water pressure head, h_r , for the three respective cases.

Cumulative uptake of water (ml)

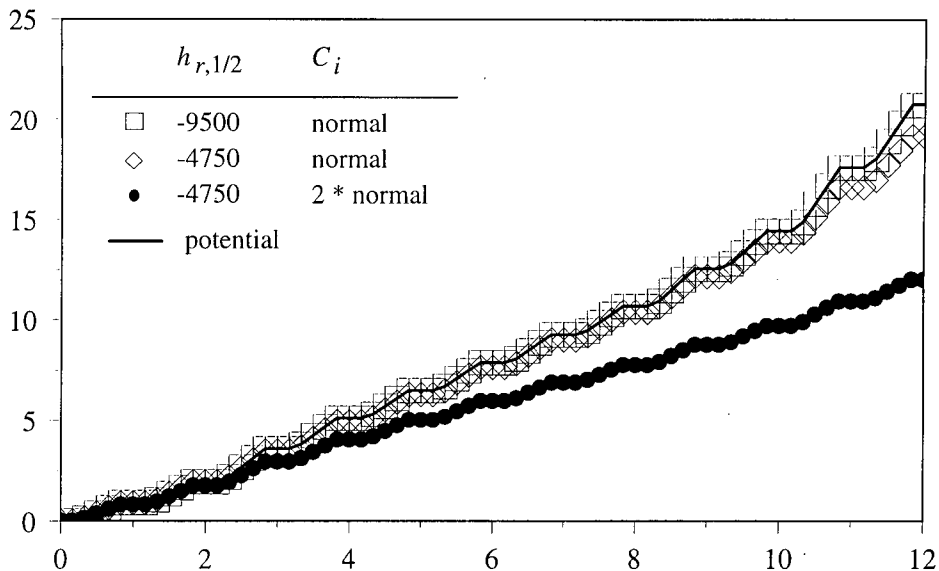


Figure 4: Cumulative uptake of water by the root system for three combinations of parameter $h_{r,1/2}$ and initial concentration C_i compared to the potential demand. Results refer to the coarse sand substrate in the sand bed system of Figure 1.

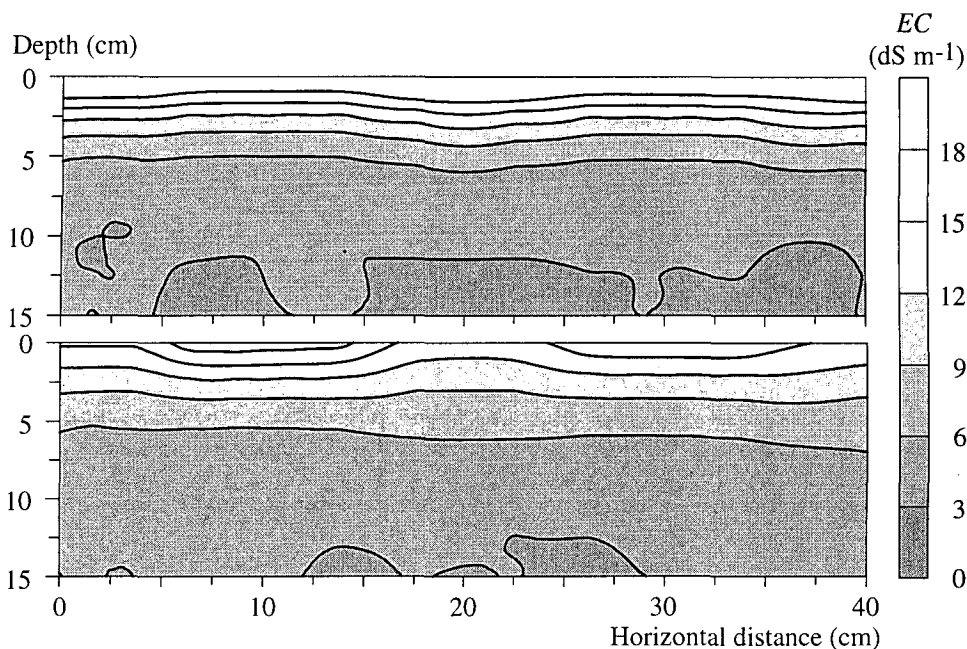


Figure 5: Electrical conductivity EC distributions after the twelve day simulation period for the coarse sand system with $h_{r,1/2} = -4750$ cm and twice the normal initial concentration for the cases without ($\sigma = 0$, top diagram) and with ($\sigma = 1$, bottom diagram) inclusion of osmotic head in water uptake equation (Eq. [6]).

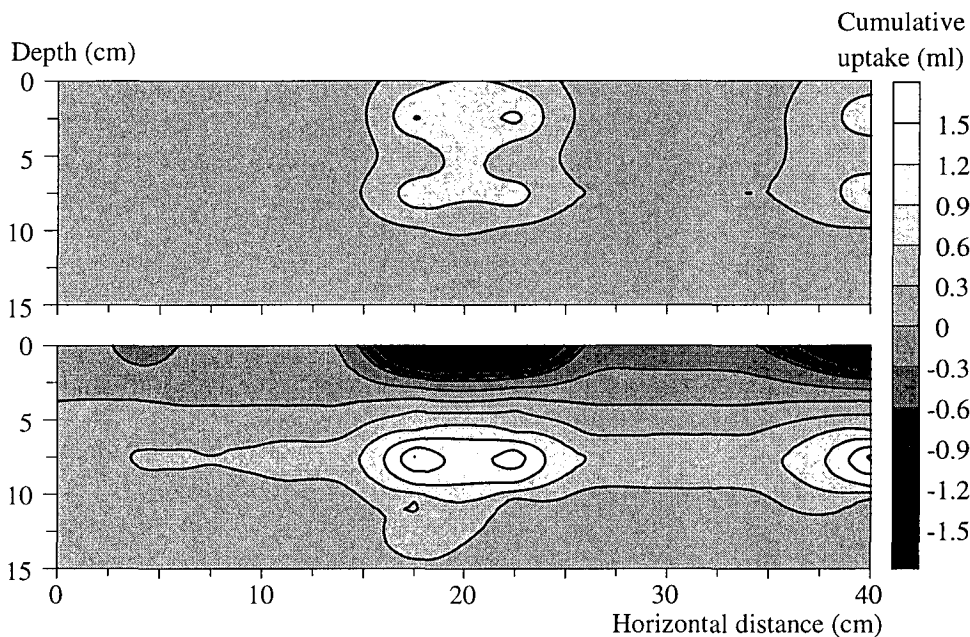


Figure 6: Cumulative water uptake distributions after the twelve day simulation period corresponding to the cases of Figure 5. A negative uptake means outflow of water from the roots, see text for explanation.