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Movement of water through the soil-plant-atmosphere system

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Abstract: The flow of liquid water from the soil into the plant depends on the plant having a lower water potential than the soil; thus the soil water potential determines the availability of soil water for diffusion into the plant. As soils dry, the water potential decreases, making it more difficult for plants to obtain the water they need to grow. Once water enters the plant through its roots, it moves through the plant vascular system to the leaves if the leaves have lower water potentials than the roots. The general flow pattern is: soil → root cells → endodermis → xylem → leaf cells → stomata → air. The water potential in the soil are gravitational, matric, osmotic and overburden. In the plant the water potential are osmotic, matric and turgor. The driving force for the movement of water in the soil and hence also towards the plant roots is constituted by the hydraulic potential gradient. Flow external to the vascular system also results from a hydraulic potential gradient. The amount of water arriving at the total root surface should be equal to the amount transpiring from the leaves, otherwise the plants will wilt. Plant response to the soil-moisture regime depends also on a large number of environmental variables such soil, plant and meteorological factors.
Keywords: soil, plant, atmosphere, water, system.

1. INTRODUCTION

The dominant distinguishing feature of the Earth is the presence of life. The most essential ingredient for life on Earth is water and most of the water is not on the land. However, a rapid long-distance system for transporting water from oceans to land is available through the atmosphere, much like the xylem system in a tree, which transports water long distances from the soil to the leaves high above the ground. This long-distance atmospheric transport system is driven unceasingly by the uneven, solar heating of the Earth. The soil, the plants and the atmosphere are all components of a physically unified and dynamic system in which various flow processes occur interdependently like links in a chain. In this system flow takes place from higher to lower potential energy, with the concept of water potential being equally valid and applicable in the plant, soil and atmosphere. The potential of water is defined as the work required to transfer a unit quantity of water from a standard reference state where the potential is taken as zero, to the location where the potential needed to be defined (Hillel D., 1971). The water potential gives then an indication of the energy level or the availability. The unit quantity in the definition of potential may be unit mass, unit volume or unit weight. In all cases, only differences in potential are significant and not the absolute value of the energy. Water moves then in our dynamic system from a position where the water potential is relatively high (a smaller quantity) to one where the water potential is relatively low. As soils dry, the water potential decreases, making it more difficult for plants to obtain the water they need to grow. The soil water potential is related to the water content of the soil. Typically soils can provide an amount of water to plants from storage that is equivalent to 5% (sands) to 20% (silt loames) of the plants rooting depth. Thus for a plant rooted to a depth of 1 m, soils can provide approximately 50-200mm of water to the plant. With evapotranspiration rates of 2-10mm day^{-1}, soils can store enough water to sustain plants for a month or more without rainfall or irrigation. Once water enters the plant through its roots, it moves through the plant vasculat system to the leaves if the leaves have lower water potentials than the roots. Since the transport resistance to mass flow in the stem xylem is usually less than the transport resistance to diffusion through the root, and the flows through both root and xylem must be equal according to conservation principles, the water potential difference from the soil to the root xylem will usually be greater than the water potential difference from the root xylem to the leaf. Water is lost from plants through pores in the leaf surfaces, called stomata. As water is transpired through the stomata, additional water is drawn through the xylem to replace it.

Description of Roots

Root system are composed of the primary root that originates as part of the developing embryo in the seed, postembryonic, shoot-borne roots, and lateral roots that emerge from all root types. Root hairs are extensions of epidermal cells and vary in length from 0.2 to 2mm, depending on the species. Root anatomy changes along the growing root (figure 1)

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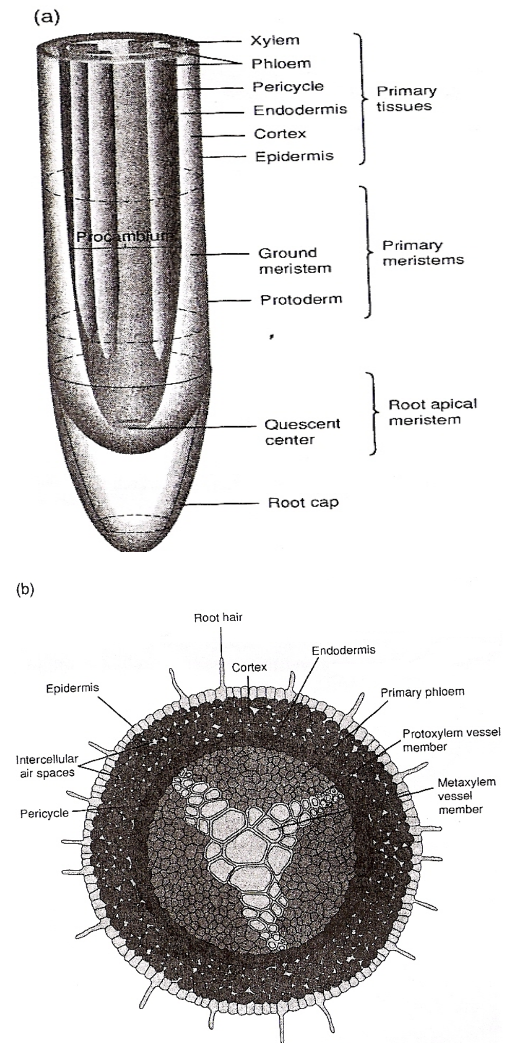

Fig. 1 Longitudinal wiew of a developing root (left) and cross section of a maturing root (right) (Reproduced after L.E. Jackson, 2005)

The epidermis is the outer layer of the root, with the protective exodermis immediately underneath it. These layers surround the cortex, which stores nutrients. The Casparian strip is a waxy substance that is present in endodermal cell walls. It forces water and nutrients to pass through the protoplasts of the endodermal cells, presumably to increase the selective uptake of nutrients. Within the vascular cylinder of the root, the xylem consists of hollow tracheids, which are important for water transport, and phloem elements, which are food-conducting tissue. Phloem differentiates in the areas between the columns of xylem cells. The pericycle is the outermost boundary of the vascular cylinder. It long-lived cells are the sites where woody secondary growth originates, as does the bark of woody roots. Water is absorbed in the liquid state by the roots from the soil. The general flow pattern is shown in figure2: soil → root cells → endodermis → xylem → leaf cells → stomata → air (the latter as vapour flow). Most of the transport (±80%) through the root and leaf cells takes place along the microcapillaries situated in the cell wall.

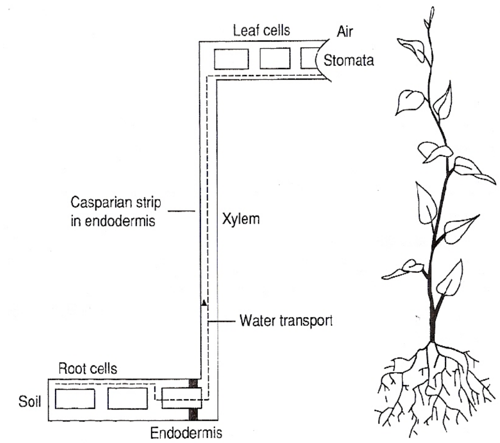

Fig. 2 Liquid transport through the plant tissues (feddes S.A., 2005)

However, the roots contain endodermis cells in which the continous system of microcapillaries in the cell walls is interrupted by the so-called Casparian strips. Consequently most of the water has to pass through the cells itself. This means that the permeability of the endodermis cell and the semipermeable membrane (plasmalemma) can be an important determinant in controlling the water flow.

Water uptake by Plants

The component potentials of the water potential in the soil are the gravitational potential, the matric potential, the osmotic potential, and in some instances, the overburden potential. The components of the water potential in the plant are the osmotic potential (resulting from the presence of dissolved salts, sugars, organic acids) the matric potential (because of the presence of water-adsorbing substances as proteins and polysaccharides), and the turgor potential. The ability to maintain a positive turgor potential under suitable conditions is a characteristic of cell membranes in living tissue. To maintain turgor, these membranes must be more permeable to water than to solutes. When the water potential Ψ, equals – 15 bar, plasmolysis is about to start and the leaf would wilt. When Ψ equals 0 the plant cell has its largest turgor potential (+12.5 bar, for example) and it has also its largest volume. This turgor pressure is then completely balanced by the osmotic potential contribution since (Gardner W.R., 1965):

$$\Psi = \Psi_{\pi} + \Psi_{p} \qquad (1)$$

where Ψ_{π} is osmotic potential and Ψ_{p} the turgor potential.

Under conditions of a steady state system in the plant cells we have the condition that the water potential in the vacuole must be equal to that in the protoplasm and to that in the cell wall. Gradients in Ψ result from the like changes in concentration of dissolved salts, in attraction of colloidal compounds or in turgor potential. In a steady state system potential differences in different parts of the system are proportional to the resistance to flow. The resistance is generally greater in the soil than in the plant, and greatest in the transition from the leaves to the atmosphere where water changes its state from liquid to vapour. Water moves then out of the leaves through the stomata by the process of diffusion. The total difference in potential between the soil and the atmosphere can amount to hundred of bars, and in arid climate can even exceed 1000 bar. The driving force for the movement of water in the soil and hence also towards the plant roots is constituted by the so called hydraulic potential gradient, i.e. the gradients of the components of matric and gravitation potential only. Flow external to the vascular system through intercellular spaces, filled with water vapour and air, also results from a hydraulic potential gradient. When air enters the xylem vessels because of a cut and thawing the continuity of water column is broken. Such vessels can no more contribute to the transport of liquid water (table 1).

Table 1 Comparison of dimensions of roots and soil pores

radius of roots:	primary	$3\cdot10^{-2}$cm
	secondary	$1\cdot10^{-2}$cm
	tertiary	$5\cdot10^{-3}$cm
length of root hair		$1\cdot10^{-1}$cm
radius root hair		$6\cdot10^{-4}$cm
diameter fine sand		$2\cdot10^{-2}$cm - $2\cdot10^{-3}$cm
	silt	$2\cdot10^{-4}$cm - $2\cdot10^{-3}$cm
	clay	$< 2\cdot10^{-4}$cm

As long as the plant does not wilt, and as long as the influx of radiation and head to the canopy results in change in phase of water only it is possible to make the assumption that a steady – state exists throughout the plant. This means that the transpiration rate is equal to the water transport through the plant and to the water uptake rate by the plant roots:

$$q = \frac{-\Delta\Psi_{root}}{R_{root}} = \frac{-\Delta\Psi_{xylem}}{R_{xylem}} = \frac{-\Delta\Psi}{R} \qquad (2)$$

where $\Delta\Psi$ represents the potential difference, R, the corresponding resistance, and q, the water flow.

We may write equation 2 for two sections of the flow path, from the root to the mesophyll cells in the leaf, and from these leaf cells to the ambient air, as follows:

$$q = \frac{\Psi_{root} - \Psi_{leaf}}{R_1} = \frac{p_{leaf} - p_{air}}{R_v} \qquad (3)$$

where Ψ_{root} is the water potential in the xylem terminals in the root; Ψ_{leaf} the water potential in the mesophyll cells; p the corresponding vapour pressure, and p_{air} the water vapour pressure in the bulk air, and R_1 and R_v the resistances for liquid and vapour flow, respectively. From thermodynamics it is known that

$$V_o d\Psi = v_o d_p \qquad (4)$$

where V_o and v_o are the specific volumes of liquid water and water vapour. Partial differentiation of (3) for constant Ψ_{root} and p_{air} gives:

$$\left(\frac{\partial q}{\partial R_v}\right)_{p_{air}} = -\frac{1}{R_v^2}\frac{\partial p_{leaf}}{\partial R_v} \text{ and}$$

$$\left(\frac{\partial q}{\partial R_1}\right)_{\Psi_{root}} = \frac{1}{R_1^2}\frac{\partial \Psi_{leaf}}{\partial R_1}$$

For an equal rate of change in resistance to liquid transport and vapour flow (dR_v=dR_1) we have from (3) and (4):

$$\frac{\left(\frac{\partial q}{\partial R_v}\right)}{\left(\frac{\partial q}{\partial R_1}\right)} = \frac{-R_1^2}{R_v^2}\frac{\frac{\partial p_{leaf}}{\partial R_v}}{\frac{\partial \Psi_{leaf}}{\partial R_1}} = -\frac{R_1^2}{R_v^2}\frac{V_o}{v_o} \qquad (5)$$

The root system of plant can be quite extensive, with a total length of several km. The total root area of an annual grass plant may be of the order of 1000 m^2, but only 1 % come into direct contact with the particle surface area of say a medium textured soil. It follows that water must move a considerable average distance in the soil before arriving at the nearest root surface (D. Hillel, 1971). The amount of water arriving at the total root surface should be equal to the amount transpiring from the leaves, other wise the plants will wilt. The flow process can be described by:

$$q = \frac{\Psi_{soil} - \Psi_{root}}{R} \qquad (6)$$

where q is the amount of water extracted per unit volume of soil per unit time, and R is the resistance.

The gradient in water potential next to a root can be calculated by solving the general flow equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left(D(\theta)\frac{\partial\theta}{\partial x}\right) \qquad (7)$$

where θ is the volumetric content, t is time, and D(θ) the soil moisture diffusivity. In cylindrical coordinates:

$$\frac{\partial\theta}{\partial t} = \frac{1}{2}\frac{\partial}{\partial r}\left(D(\theta)\cdot r\frac{\partial\theta}{\partial r}\right) \qquad (8)$$

where r is the radial distance from the axis of the root. This suggests that soil water can move towards the root over distances of several mm or cm. When we assume that the stomata close over a rather narrow range of Ψ_{leaf}, the value of which, Ψ_w, depends on the crop, we can write (3) as follows:

$$q = \frac{\Psi_{root} - \Psi_w}{R}$$

were q_w describes the rate at which the soil-plant system can supply water to the leaves under the limiting conditions of wilting. Stage of growth is an important factor in determining the water requirement. Evapotranspiration increases gradually from planting time to maturity and thereafter it decreases gradually.

We may conclude that root water uptake depends on a number of factors such as soil hydraulic conductivity, rooting depth, root density distribution, soil moisture pressure head, demand set by the atmosphere (potential transpiration) on the plant system, and the presence of a water table. This indicates that it is not simple to model water uptake by roots, nor to generalize on the effect of a single modification at the root zone. Root water uptake can be represented as a sink term that is added to the vertical water flow equation through the soil. This macroscopic way of solving the root water uptake problem is to combine the continuity equation of water flow with a sink term representing water extraction by plant roots:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial v}{\partial z} - S \qquad (9)$$

where θ, t, v_z is the Darcian soil water flux density, and S (cubic centimetres per cubic centimetre per day) is the root water uptake. Combination of eqns. Darcy's law with eqns (9) results the Richard equation:

$$\frac{\partial \theta}{\partial t} = C(h)\frac{\partial h}{\partial t} = \frac{\partial\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right]}{\partial z} - S(z) \qquad (10)$$

where C is the differential water capacity (dθ/dh) (per centimeter). Under optimal moisture conditions, the maximum possible root water extraction rate Sp(z), integrated over the rooting depth, is equal to the potential transpiration rate, Tp (centimetres per day), which is governed by atmospheric conditions:

$$S_p = \frac{T_p}{|z_{root}|} \qquad (11)$$

where T_p is the potential transpiration rate (centimeters per day) and $|z_{root}|$ is the root zone depth (centimeters). The potential root water extraction rate at a certain depth, $S_p(z)$ (per day), may for nonhomogeneous root distributions be determined by the root length density $L_{root}(z)$ (centimetres per cubic centimeter) as fraction of the total root length density over the rooting depth $|z_{root}|$ (centimeters), according to:

$$S_p(z) = \frac{L_{root}(z)}{\int_{-z_{root}}^{0} L_{root}(z)\partial z} T_p \qquad (12)$$

Under nonoptimal conditions, i.e., too dry, toowet, or too saline a reduction is applied (R.A. Feddes, 2005).

CONCLUSIONS

The state and movement of water in the soil, plant and atmosphere are affected by a complex set of interactions and of processes which occur simultaneously at different rates. Water movement from the soil, through the plant, and to the atmosphere occurs along a path of continuously decreasing potential energy. This path includes a number of distinct segments each of which can be described in terms of a flow equation. The first link in this chain is the flow of water in the unsaturated soil surrounding the root, and as such it can affect the overall flow process. Plant response to the soil-moisture regime depends also on a large number of environmental variables such soil factors, plant factors, and such meteorological factors.

Precipitation falls on a field and infiltrates into the soil. The infiltrated water may be stored in the soil matrix, evaporated from the soil surface, transpired from plants, or drain below the plant roots. Water that drains below the plant roots becomes part of the groundwater system and may reenter rivers.

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