IPS-141
Sensory and Physiological Ecology of Plants

X: Water Relations

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Outline

Water and plants

Water relations

Water potential in nature

Water in the soil

Water and plants

Water in plants

- Protoplasma: 85–90% water.
- Soft leaves: 80–90% water.
- Ripe seeds: 10–20% water.
- Life originated in the water.
- Conquest of land: required adaptation to dryness.

Poikilohydric plants

- Primitive ‘plants’ (fungi, some algae and lichens).
- Mosses from dry habitats.
- A few vascular plants (e.g. some vascular cryptogams and some ferns, in the angiosperms the so called “resurrection plants”).
- Strategy: dehydration tolerance.
- Small cells, no vacuoles.
- Water content follows environmental fluctuations.
- Dryness $\rightarrow$ resting state.
- Wetness $\rightarrow$ active state.

Homoiohydric plants

- Many mosses, most vascular plants.
- Strategy: dehydration avoidance.
- Big cells with big vacuoles.
- Cuticle and stomata.
- Dryness $\rightarrow$ stomatal closure.
- Parallel:

  plants: poikilohydric vs. homoiohydric.
  animals: poikilothermic vs. homoiothermic.

Why do plants need water?

- Biochemical and chemical reactions occur in a water medium.
- Turgor (*nestej□nnitys*) or pressure is needed for cell expansion and structural rigidity of non-lignified organs like leaves.
- Photosynthesis.
- Transport medium.
- Temperature regulation (evaporative cooling).

Water relations

Movement of water

Diffusion No barriers. Force: difference in concentration.

Bulk flow No barriers. Force: difference in hydrostatic pressure.

Osmosis Semipermeable barrier or membrane. Force: water potential (result of both concentration and pressure differences).

Relative water content

Relative water content (*suhteellinen vesipitoisuus*), as percent (RWC, or R).

$$R = 100 \frac{M_\mathrm{f} - M_\mathrm{d}}{M_\mathrm{t} - M_\mathrm{d}}$$

where:

M_f: fresh weight,

M_d: dry weight,

M_t: (full-)turgor weight. (Fully hydrated weight.)

R gives the actual water content relative to the maximum water content of the tissue.

Water potential

- Water potential (Ψ) is a way to specify the different kinds of forces acting on water in the soil, in the plant, and in the atmosphere.
- Allows to express forces in the same units, which is convenient.
- It is derived from the chemical potential of water:

$$\Psi = \frac{\mu_\mathrm{w} - \mu_\mathrm{w}^0}{\overline{V}_\mathrm{w}^0}$$

  where μ is chemical potential and $\overline{V}_\mathrm{w}$ is the partial molar volume of pure water.
- μ has as units J mol^{-1} (Joules per mole, energy per mole of substance, or work per mole of substance). $\overline{V}_\mathrm{w}$ has as units $\mathrm{m}^3\ \mathrm{mol}^{-1}$.

Water potential

- The driving force for the movement of water across membranes is the difference in free energy.
- It is common to use water potential (Ψ) (*vesipotentiaali*) for expressing the free energy content of the water.
- Water potential is defined as free energy per unit volume of water.
- The potential of pure water at standard conditions is zero. ($\Psi^0 = 0$, the zero as superscript means standard conditions: 25 C and atmospheric pressure)
- It is expressed in pressure units (MPa, mega-Pascals; 1 MPa = 10 bar).

Water potential

- The water potential of water that is not free or pure, is less than zero. ($\Psi < 0$).
- Water potential measures work needed.
- Units: work volume^{-1} (= energy volume^{-1}) which is equivalent to pressure.
- $\mathrm{J\ m^{-3} = N\ m\ m^{-3} = N\ m^{-2} = Pa}$
- N: Newton, Pa: Pascal, J: Joule (all SI units).

Water potential

The water potential (Ψ) of a cell is given by

$$\Psi = \psi_\mathrm{s} + \psi_\mathrm{m} + \psi_\mathrm{p}$$

where ψ_s is the solute potential, ψ_m is the matric potential and ψ_p is the pressure potential.

In tall trees, of more than 10 m, then another component becomes significant: gravitational potential (ψ_g) and must be added to the above equation.

Water potential

$$\Psi = \psi_\mathrm{s} + \psi_\mathrm{m} + \psi_\mathrm{p}$$

- Their origin is what makes these components different.

ψ_s The solute or osmotic potential. Depends on the ions, and undissociated molecules in solution.

ψ_m The matric potential. Depends on colloidal particles or surface interactions, for example soils and cell walls.

ψ_p In a compartment of restricted volume, or almost fixed volume it counterbalances the other components.

Equilibrium

$$\Psi_{\mathrm{apo}} = \Psi_{\mathrm{vac}} = \Psi_{\mathrm{cyt}}$$

Water potential is in equilibrium between apoplast, vacuole, and cytoplasm.

- The components are different.
- In the vacuole ψ_{s} and ψ_{p} predominate.
- In the cytoplasm ψ_{m} predominates because of colloidal particles.
- In the apoplast (cell wall) ψ_{m} predominates because of surface interactions.

Water potential changes

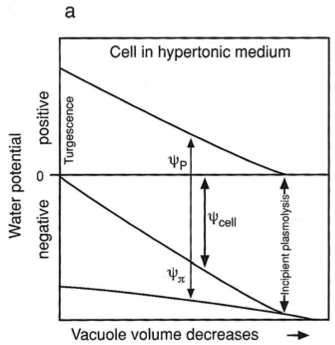


Fig. 4.3a,b. Water potential of vacuolated cells in a hypertonic medium (**a**) and of vacuolated cells drying in air (**b**). As water loss proceeds the osmotic potential Ψ_π becomes more negative and the pressure potential Ψ_P drops from positive values to zero; the water potential of a cell equals the summation of Ψ_π and Ψ_P. (Schematic representation, after Höfler 1920; Barrs 1968; Kyriakopoulous and Larcher 1975; Pospišilová 1975). For specific parameters of mosses and lichens, see Proctor et al. (1998), for desiccation-tolerant bryophytes, see Proctor (2000)

(from Larcher 2003).

Movement

- Water tends to move from regions of high water potential like soil and roots to regions of low water potential like leaves and the atmosphere. (But there are exceptions.)
- In the xylem the main component of Ψ is negative pressure.
- In leaf cells ψ_p is usually positive (turgor).

Remember!

The driving force for water movement in the xylem is not the water potential, but it is hydrostatic pressure because it is bulk flow rather than diffusion through a membrane. However, the cells near the xylem vessels are at a similar water potential to the xylem sap because they are separated by a membrane.

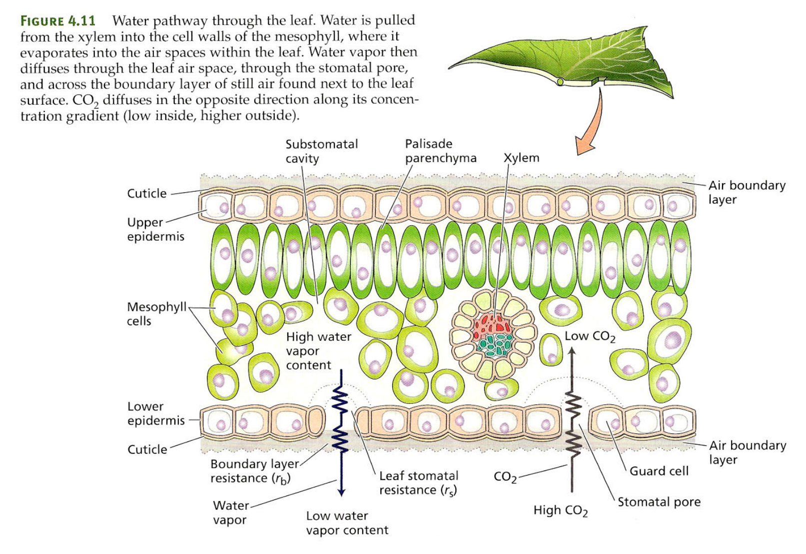
Water flow in the plant

- Long distance movement of water in the plant occurs by bulk flow.
- Water in the xylem is under tension.
- The source of tension in the xylem is the negative pressure that develops in the walls of mesophyll cells when water evaporates.
- The cell wall acts like a very fine capillary wick soaked with water.
- Surface tension in the crevices of the wall induces a negative pressure in the water.
- Thus the motive force for xylem transport of water is generated at the air-water interfaces within the leaf.

Water flow out of the leaf

- The water that evaporates from the mesophyll cell walls builds up the water vapour concentration in the intercellular spaces inside the leaf (the mesophyll air space).
- The concentration of water vapour (water vapour pressure, or molar fraction) is usually assumed to be saturated at the temperature of the leaf.
- Water vapour moves from the leaf interior to the atmosphere through stomata by diffusion.
- The layer of still air on the surface is called boundary layer, and movement of vapour through this layer is mostly by diffusion.
- The thickness of the boundary layer depends on the wind speed and size of the leaf.

Water path out of leaf



(from Taiz and Zeiger 2006).

Stoma

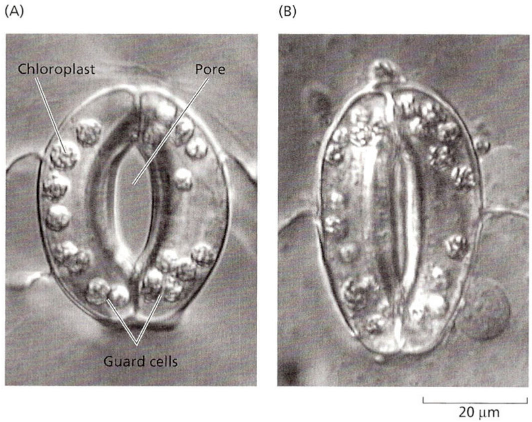


FIGURE 18.8 Light-stimulated stomatal opening in detached epidermis of *Vicia faba*. Open, light-treated stoma (A), is shown in the dark-treated, closed state in (B). Stomatal opening is quantified by microscopic measurement of the width of the stomatal pore. (Courtesy of E. Raveh.)

(from Taiz and Zeiger 2006).

Water flow into the roots

- In the roots water cannot move all the way through the apoplast.
- The Casparian bands of endodermis walls prevents it.
- Water must move at least part of the way through the symplast (the inside of the cells).
- Consequently the water must cross at least two membranes.
- Water movement through membranes is regulated by aquaporins (water permeable pores that open and close under metabolic control).
- The hydraulic conductivity is not constant.

Water path in root

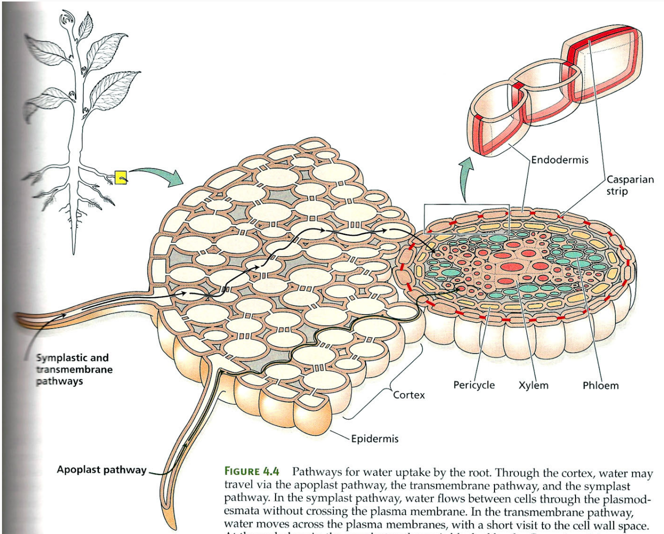
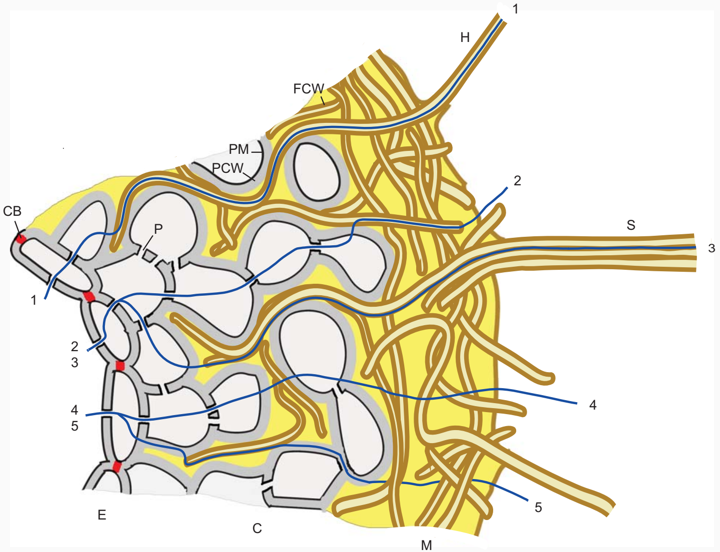


FIGURE 4.4 Pathways for water uptake by the root. Through the cortex, water may travel via the apoplast pathway, the transmembrane pathway, and the symplast pathway. In the symplast pathway, water flows between cells through the plasmodesmata without crossing the plasma membrane. In the transmembrane pathway, water moves across the plasma membranes, with a short visit to the cell wall space. At the endodermis, the apoplast pathway is blocked by the Casparian strip.

(from Taiz and Zeiger 2006).

Water path in ectomycorrhiza



(from Lehto and Zwiazek 2011).

Water potential in nature

Water potential profiles

- In transpiring plants there is a gradient in water potential.
- Highest (less negative) water potentials occur in the soil, and lowest water potentials usually at the top of the plant.
- At night the gradient collapses or gets very small because there in little transpiration.
- As the soil dries the water potential in the plant also decreases.

Water potential profiles

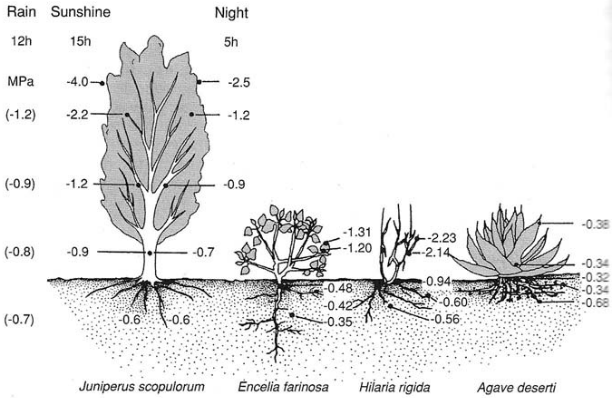
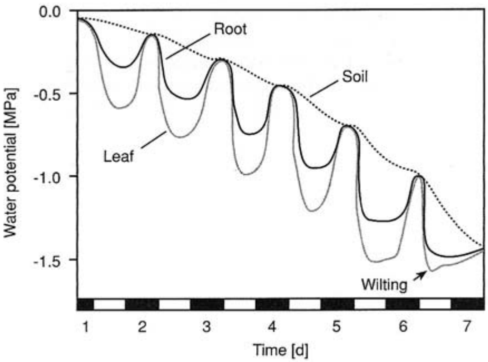


Fig. 4.11. Water potential profiles (MPa) in plants with different growth forms. For *Juniperus scopulorum*, a tree-like juniper of the arid regions of western N. America, measurements were taken in September on a sunny and a rainy day, and at night following a sunny day. For *Encelia farinosa*, a C_3 subshrub, *Hilaria rigida*, a C_4 tussock grass, and *Agave deserti*, a leaf succulent of the semi-desert in California, the water potentials were measured at the time of maximal transpiration. (After Wiebe et al. 1970; Nobel and Jordan 1983)

(from Larcher 2003).

As soil dries...

Fig. 4.26. Schematic diagram of the gradual drop in water potential of leaves, roots and soil during one week of drought. The greatest daily fluctuation occurs in the leaves, which are exposed to transpiration stress throughout the day. The water balance does not fully recover during the night (*dark bars*), thus the values of the predawn water potential become lower day by day. (After Slatyer 1967)



(from Larcher 2003).

Water in the soil

Water in the soil

- The size of pores in soils depends on the size of the soil particles.
- Sand is coarser than clay.
- From large size pores water drains quickly.
- In very small pores water is retained very tightly by capillary forces generating a tension (negative ψ_{p}).
- Water is most useful to plants if it is in medium sized pores.
- Water moves in the soil by bulk flow.
- Driving force in the soil is, like in the xylem, hydrostatic pressure (ψ_{p}).

Different soils

Soil	Particle diameter (µm)	Surface area ($m^2\ g^{-1}$)
Coarse sand	2000–200	<1
Fine sand	200–20	1–10
Silt	20–2	10–100
Clay	<2	100–1000

(adapted from Taiz and Zeiger 2006)

Take into account that most soils consist in a mixture of particles of different sizes and may also contain organic matter (e.g. humus).

Water content in soils

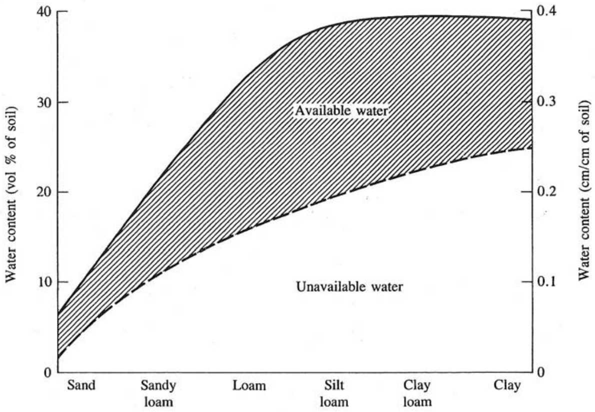


Figure 6.1 Diagram showing the relative amounts of available water in soils ranging in texture from sands to clays. Permanent wilting percentage, --; *in situ* field capacity, ——. Amounts are expressed as percentages of soil volume and as centimeters of water per centimeter of soil depth. (After Cassell, 1983; from Kramer, 1983a, by permission of Academic Press.)

Water available and unavailable to plants in different types of soils (from Kozlowski et al. 1991).

Water potential in soils

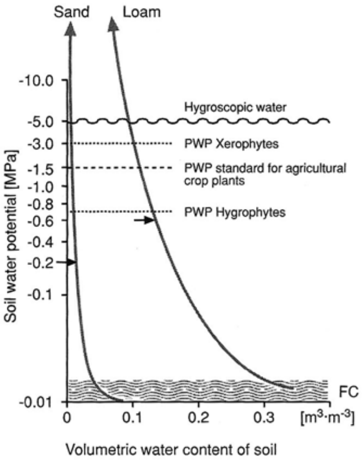


Fig. 4.6. Diagram showing the relationship between water potential (logarithmic scale) and water content of a sandy and a loam soil. The conventional threshold value for field capacity (FC) is –0.015 MPa, for permanent wilting (PWP) –1.5 MPa; at values more negative than –5 MPa there is only hygroscopically bound water. The average values shown for different plant types depend on the type of soil (soil texture, pore size) and vegetation; however, they may also be lower when plants are adapted to water deficiency. The *arrows* are referred to in the text. (After Kramer 1949; Laatsch 1954; Slavíková 1965)

Water potential in two different types of soils (from Larcher 2003).

Water uptake by roots

$$J_{\text{water}} = S \frac{\Psi_{\text{soil}} - \Psi_{\text{root}}}{\sum r}$$

where J_{water} is the flow rate (flow per unit time) of water from the soil into the root, S is the exchange area between soil and root (active root surface area), Ψ is water potential, and $\sum r$ the sum of all transfer resistances.

- Although the driving force is $\Delta\Psi$, other factors also affect the total flow rate of water between the soil and the plant.

Saline soils

- In saline soils the soil solution contains a high concentration of dissolved solutes.
- In this type of soils the solute potential (ψ_s) is an important component of the soil water potential (Ψ_soil).

Driving forces

- Soil water moves by bulk flow and the driving force is the difference in pressure ($\Delta\psi_{\mathrm{p}}$).
- Through the root water moves by diffusion through cell membranes and the driving force is the difference in water potential ($\Delta\Psi$).
- In the xylem water moves by bulk flow and the driving force is the difference in pressure ($\Delta\psi_{\mathrm{p}}$).
- From the leaf air spaces to the atmosphere near the leaf surface water vapour moves by diffusion (but not across a membrane), so the driving force is the difference in water vapour concentration (Δe).

Driving forces

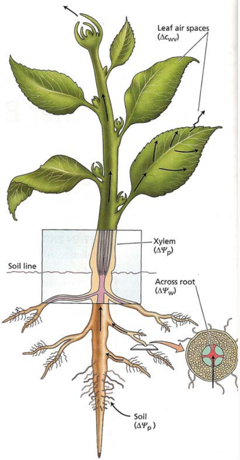


FIGURE 4.1 Main driving forces for water flow from the soil through the plant to the atmosphere: differences in water vapor concentration (Δc_{wv}), hydrostatic pressure ($\Delta \Psi_p$), and water potential ($\Delta \Psi_w$).

Driving forces for water movement in different parts of the soil-plant-atmosphere continum (from Taiz and Zeiger 2006).

References

References

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