Plant water balance

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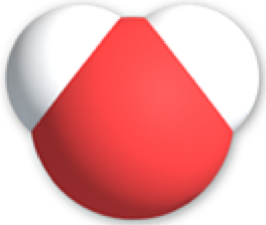
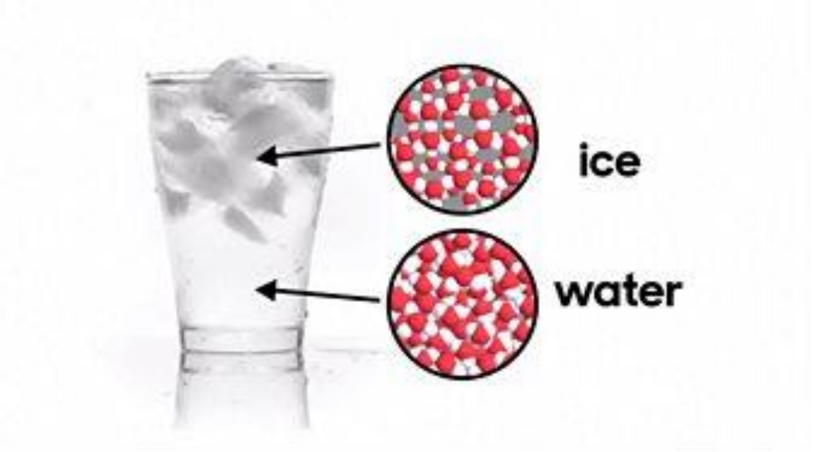
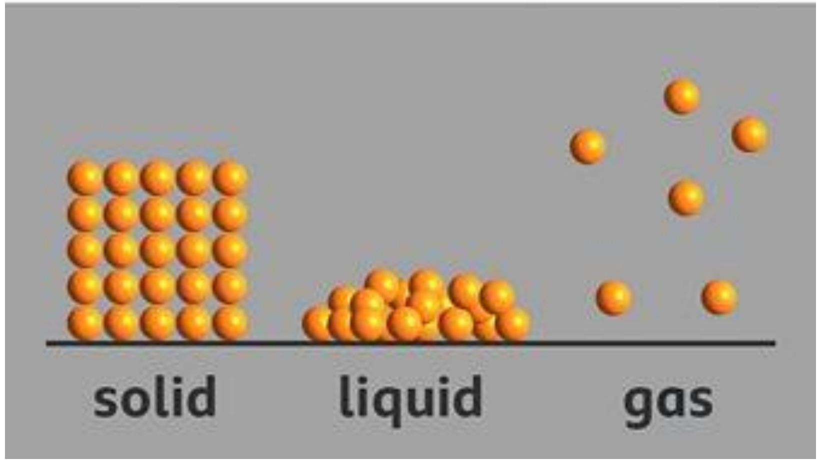
Warming Question： What is water?



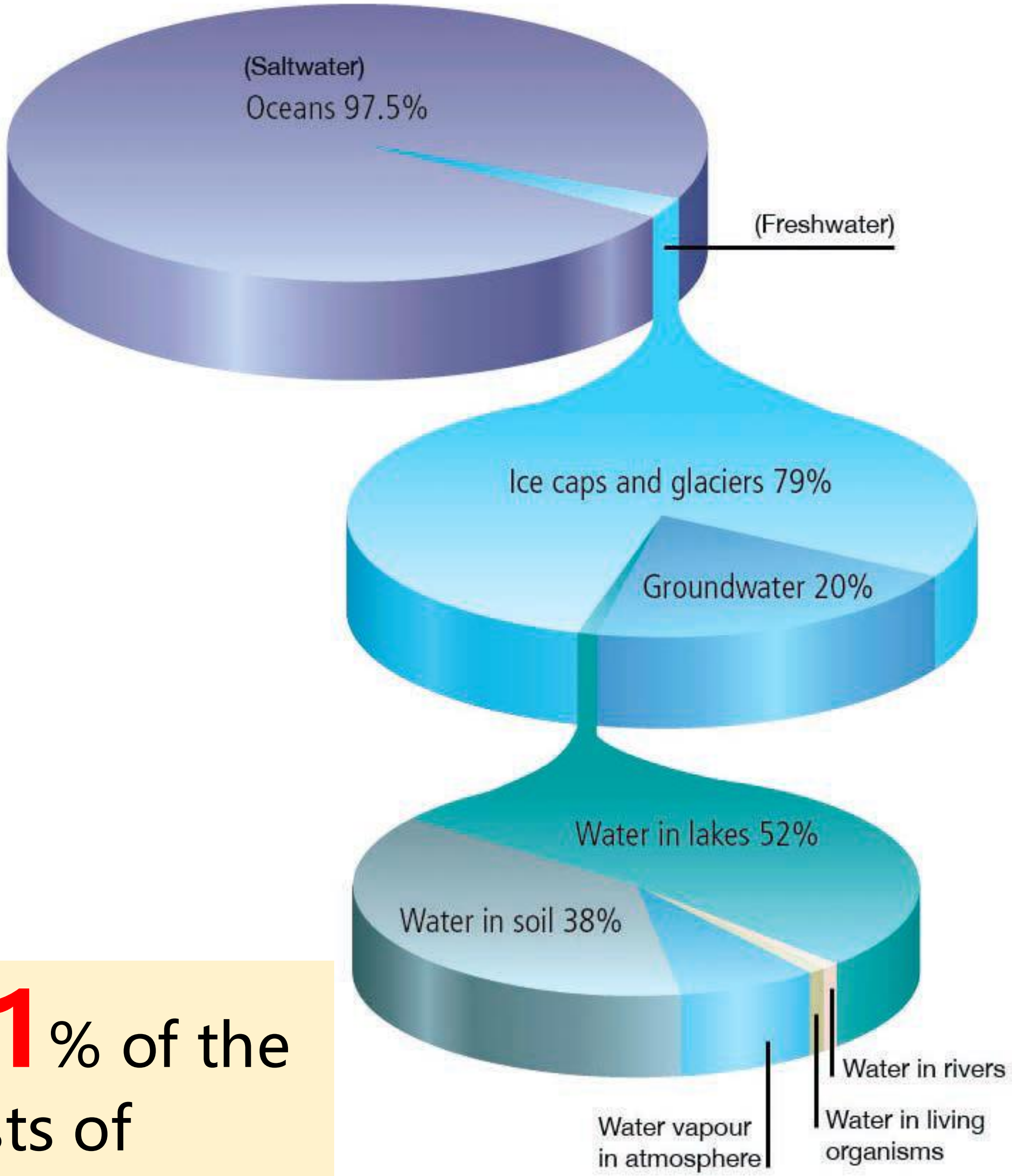
- ✓ **Inside a water molecule: 2H and 1O**
- ✓ **It has special properties:**
  - i. **It exists in the solid, liquid and gas states at normal temperatures on Earth.**
  - ii. **At 4°C water is at its most dense. Below this temperature, ice is able to float on liquid water.**
  - iii. **Water dissolves many substances, including salts in the sea and proteins in living things.**
  - iv. **Water has a high surface tension, allowing some small insects to walk on its surface.**





Warming Question： What are the roles of water in life?

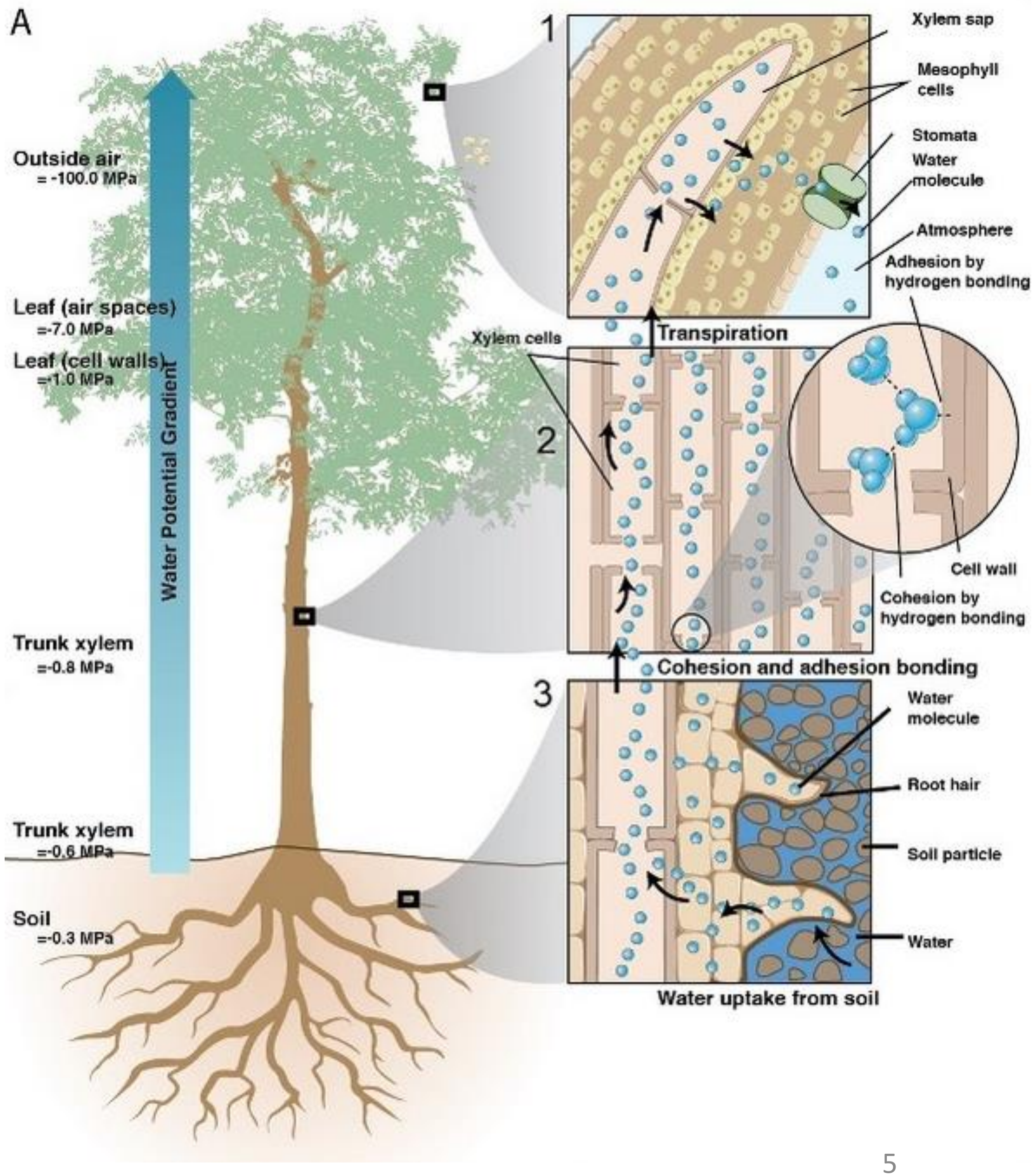
- ✓ **Component of cells**
- ✓ **Reactant of the metabolic process**
- ✓ **Supporter of biochemical reactions**
- ✓ **Carrier of material (and energy) transport**
- ✓ **…**



In simplest terms, water makes up about **71**% of the Earth’s surface, while the other 29% consists of continents and islands.

Outline

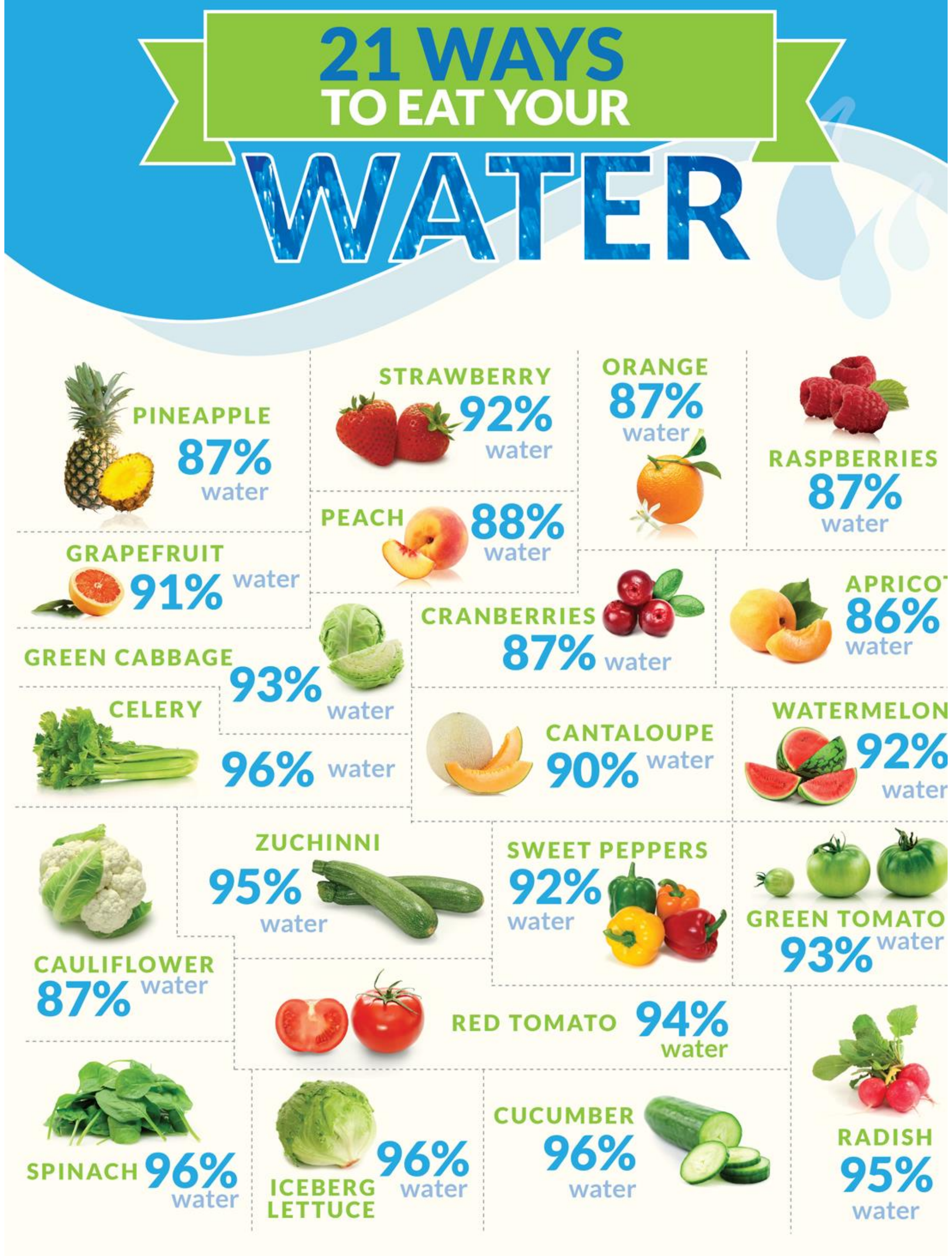
- Water status of plants
- Availability of water
- Water uptake from soil by roots
- Water escapes from plants
- Water transport through plants
- Water Use & Stress



Water status of plants

How to express the water status of plants?

1. Water content



1. Water content

Water content on a **wet-weight basis** (WC, w.b.) is widely used, and it is adopted by the International Seed Testing Association for the expression of seed water content.

$$WC_{(w.b.)} = \frac{fresh\ weight - dry\ weight}{fresh\ weight} \times 100$$

Question: When the tissue of 80% WC (% w.b.) goes to 70% and 60%, respectively, due to the soil dry, how much plant water actually lost?

Answer: 41.7% and 62.5 %

WC (w.b.) is not linear expression of water content in tissues.

1. Water content

A **dry weight basis** water content is a linear expression of water content

$$WC_{(g\ g^{-1}\ dw)} = \frac{fresh\ weight - dry\ weight}{dry\ weight}$$

When the samples are very dry (< 15 % WC), the difference between WC (% w.b.) and WC (g g^{-1} dw) is small, and the WC (% w.b.) can be converted to WC (g g^{-1} dw):

$$WC\ (g\ g^{-1}\ dw) = WC\ (\%\ w.b.)\ /\ (100 - WC\ (\%\ w.b.))$$

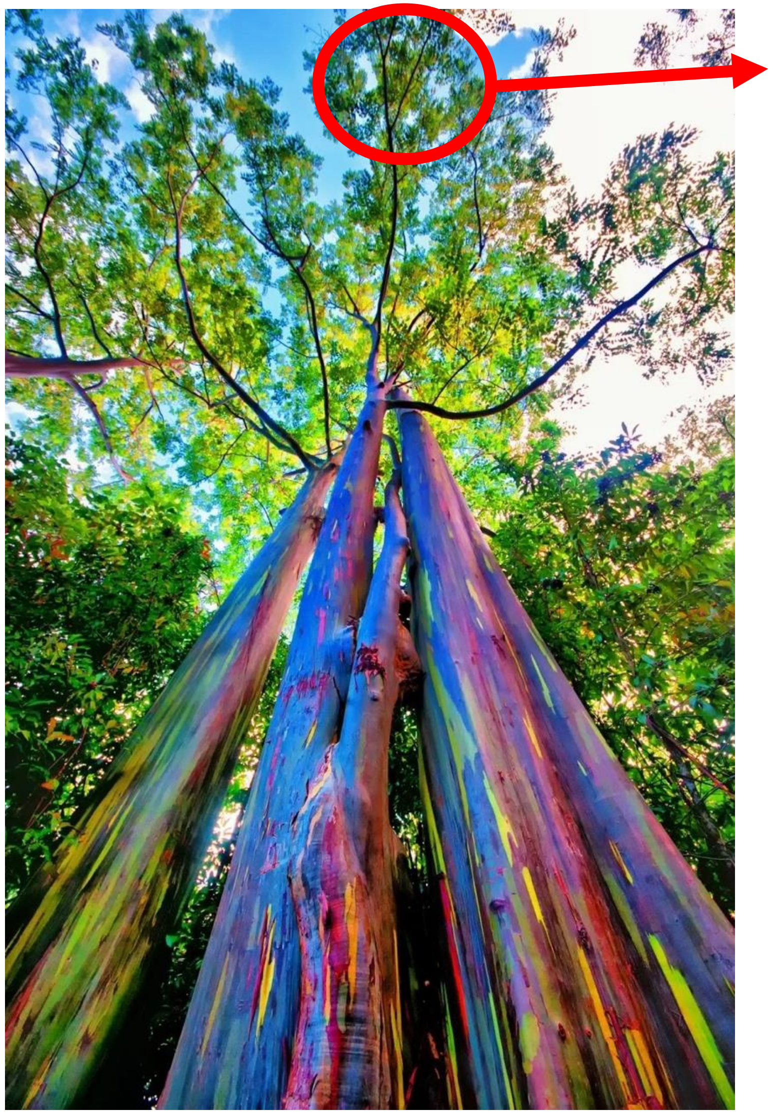
1. Water content

Relative water content (RWC) is another widely used mass-based parameter, especially in a pressure volume analysis. RWC is calculated using water content at given time divide by water content at full turgor (water saturated tissue):

$$RWC = \frac{fresh\ weight - dry\ weight}{weight\ at\ full\ turgor - dry\ weight}$$

Any problem ?

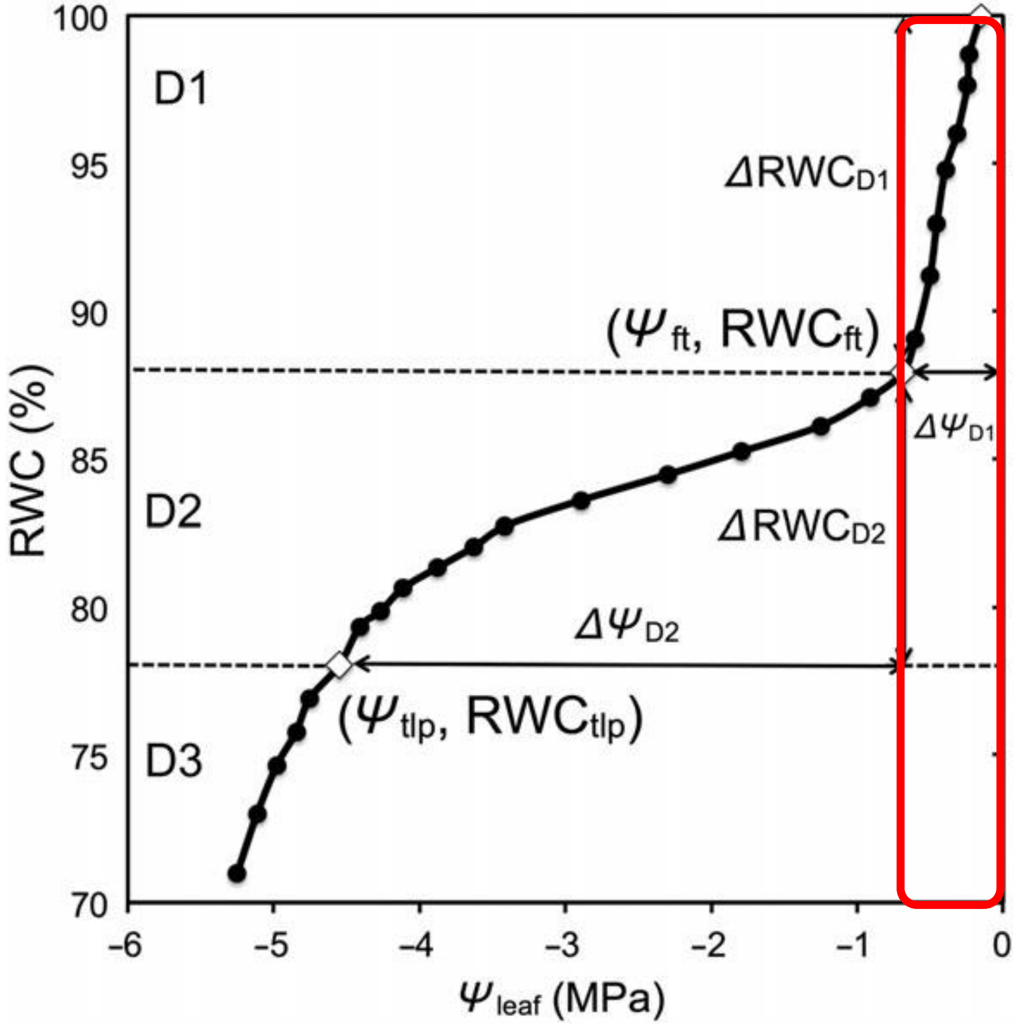
1. Water content



Water content at full turgor?

Water content after full hydration in water (plant segments hydrated in distilled water for 4-6 hours or over night) is typically used.

1. Water content



Nguyen et al., 2015

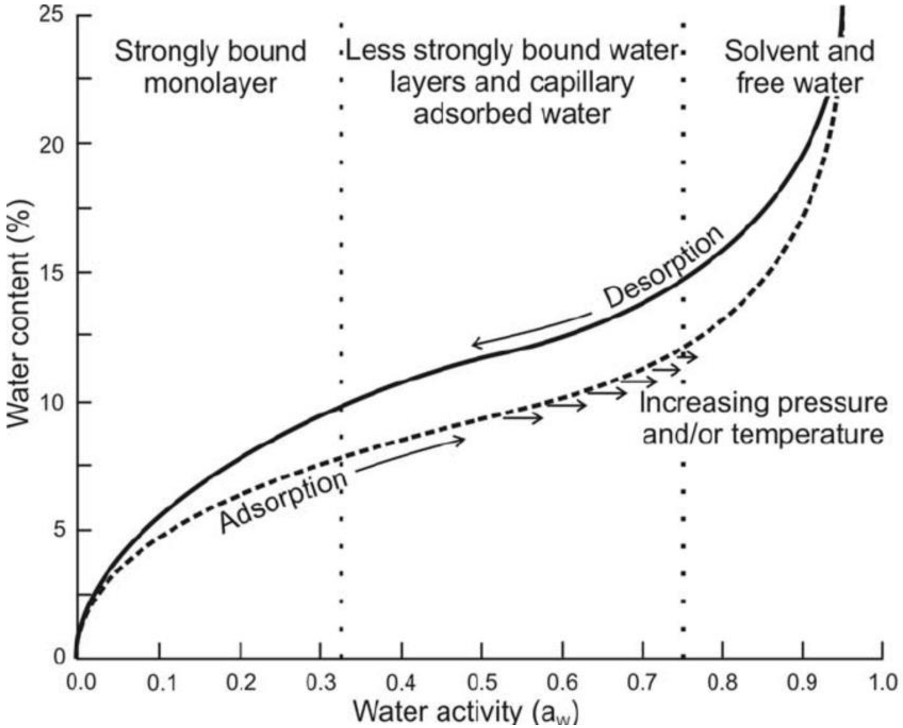
However, some plant tissues do contain intercellular water after full hydration in the lab.

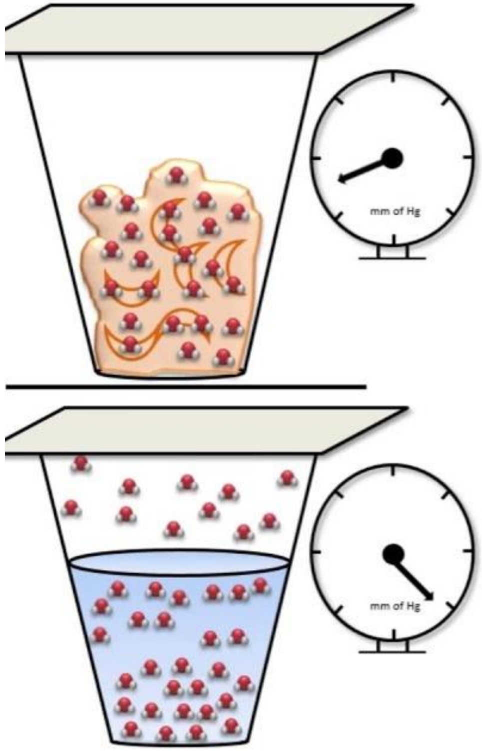
1. Water content

1. How do tissue components (proteins, carbohydrates, lipids et al) influence water contents?
2. Can water content reflect drought tolerance abilities when different tissues, the same tissues of different genotypes or species are compared? Why?

2. Thermodynamic measures for tissue water status

Water activity measured as the ratio of vapor pressure of water in a system to the vapor pressure of pure water at the same temperature.

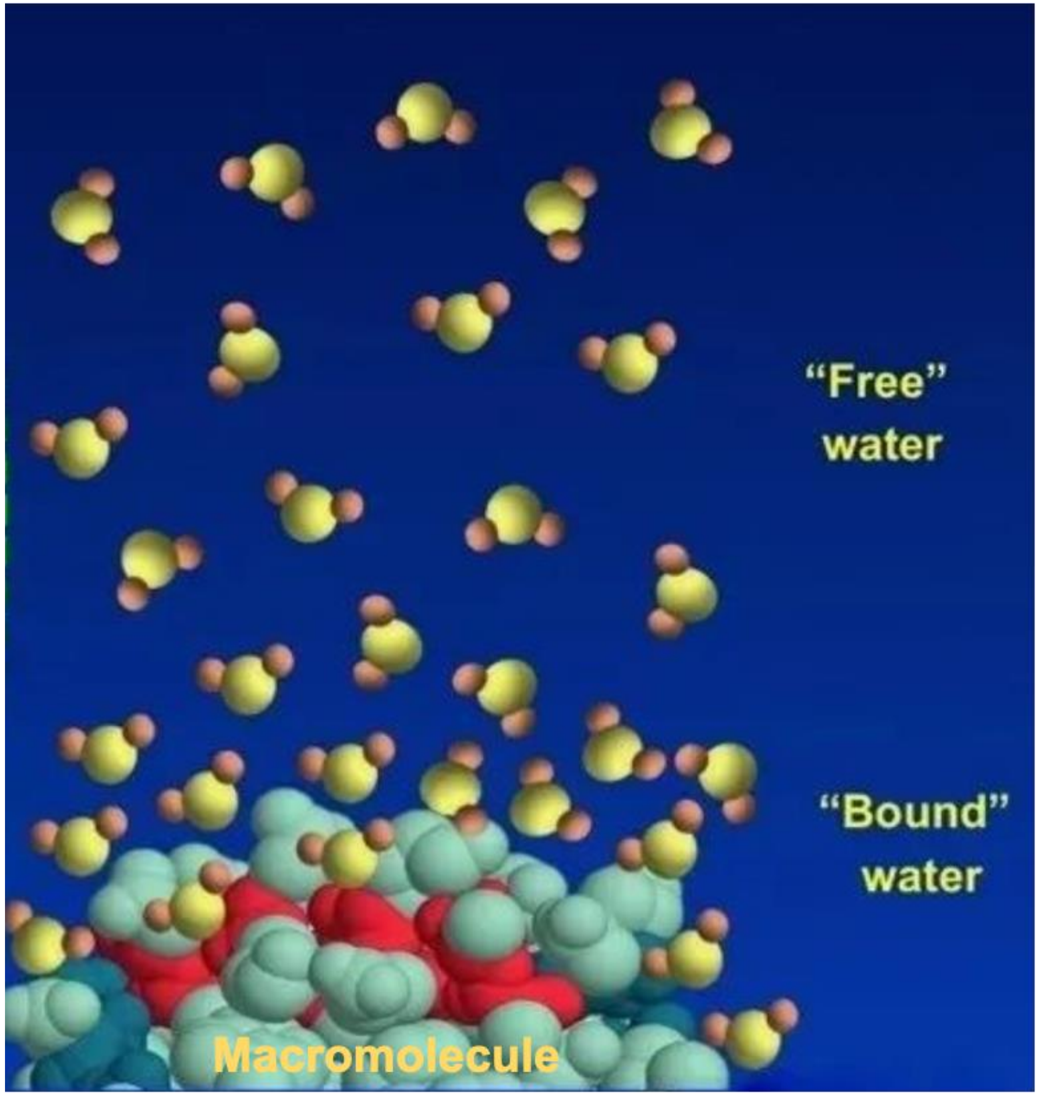




However, water activity of fresh tissues may vary only between 0.980 and 0.996, which is not useful for the expression of tissue water status in most water relative studies.

3. Forms of Water in Plant Cells

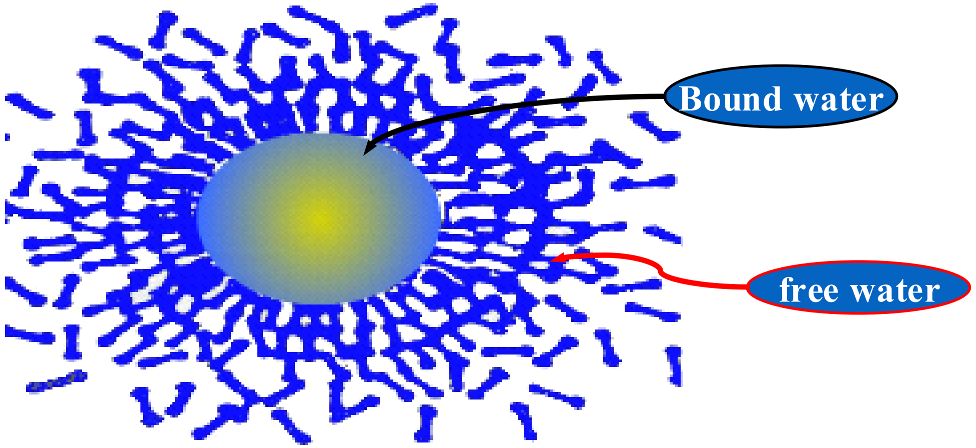
Feature	Free Water (自由水)	Bound Water (结合水)
Definition	Water that moves freely within the cell and intercellular spaces	Water physically or chemically bound to macromolecules (proteins, polysaccharides)
Physical State	Low viscosity, freezes at 0°C, high fluidity	High viscosity, does not freeze easily, low fluidity
Function	**Solvent:** Medium for biochemical reactions **Transport:** Moves nutrients/hormones	**Structure:** Component of the protoplasm **Protection:** Maintains protein stability



3. Forms of Water in Plant Cells

Free water vs Bound water

Relationship with Metabolic Activity



- **Higher free water → stronger metabolic activity**
- **Higher bound water → reduced metabolic activity**

The ratio of free water to bound water reflects the metabolic activity of cells.

In situations such as dormant seeds, overwintering plants, drought or salt stress, the ratio of free water to bound water decreases.

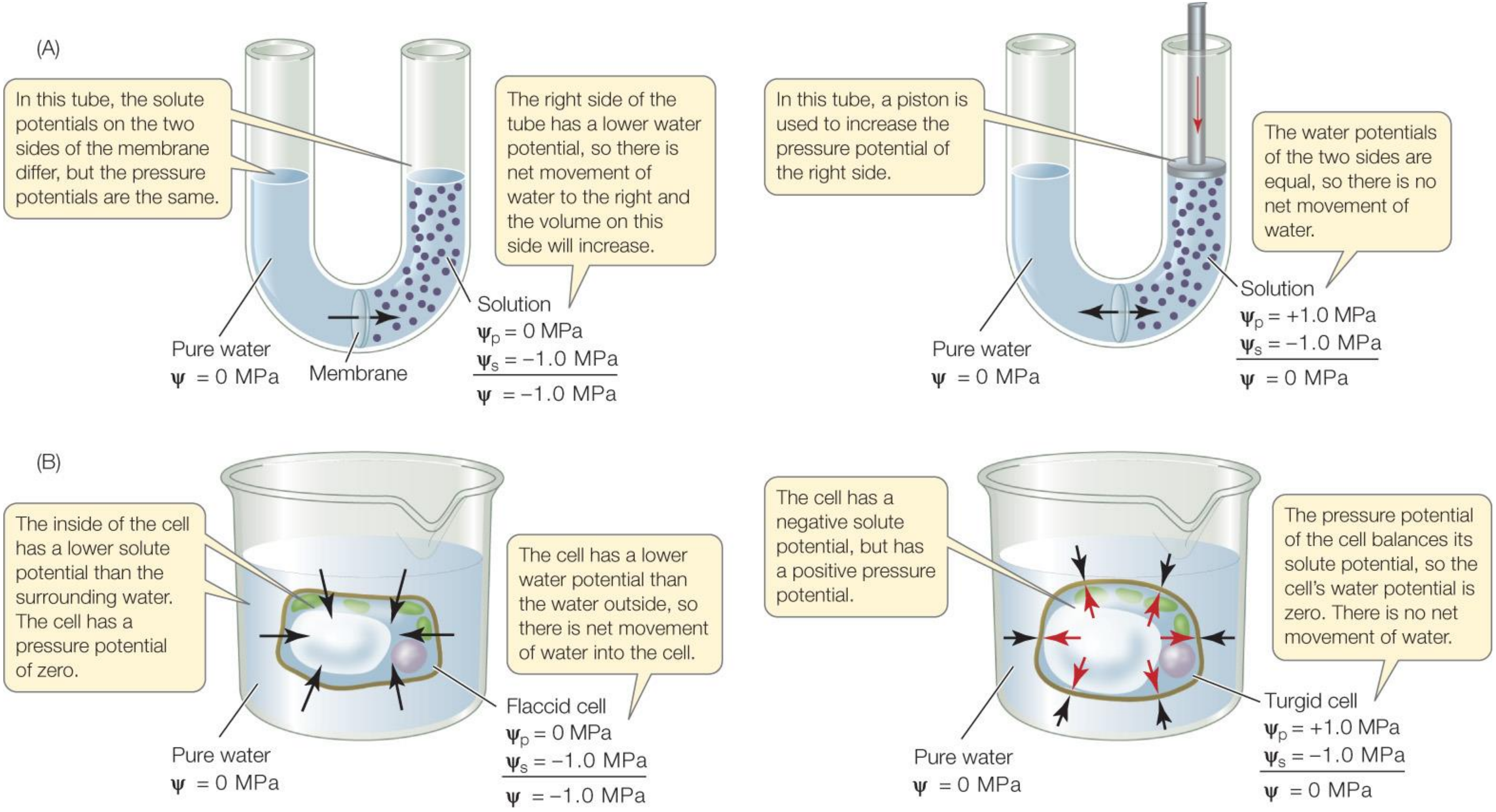
4. Water potential

From a **Physical Chemistry** perspective: water potential is proportional to the chemical potential of water in a system. Therefore, water potential is actually the potential energy of water per unit mass.

Plant physiologist: water potential is the tendency of a solution (water plus solutes) to take up water from pure water across a membrane.

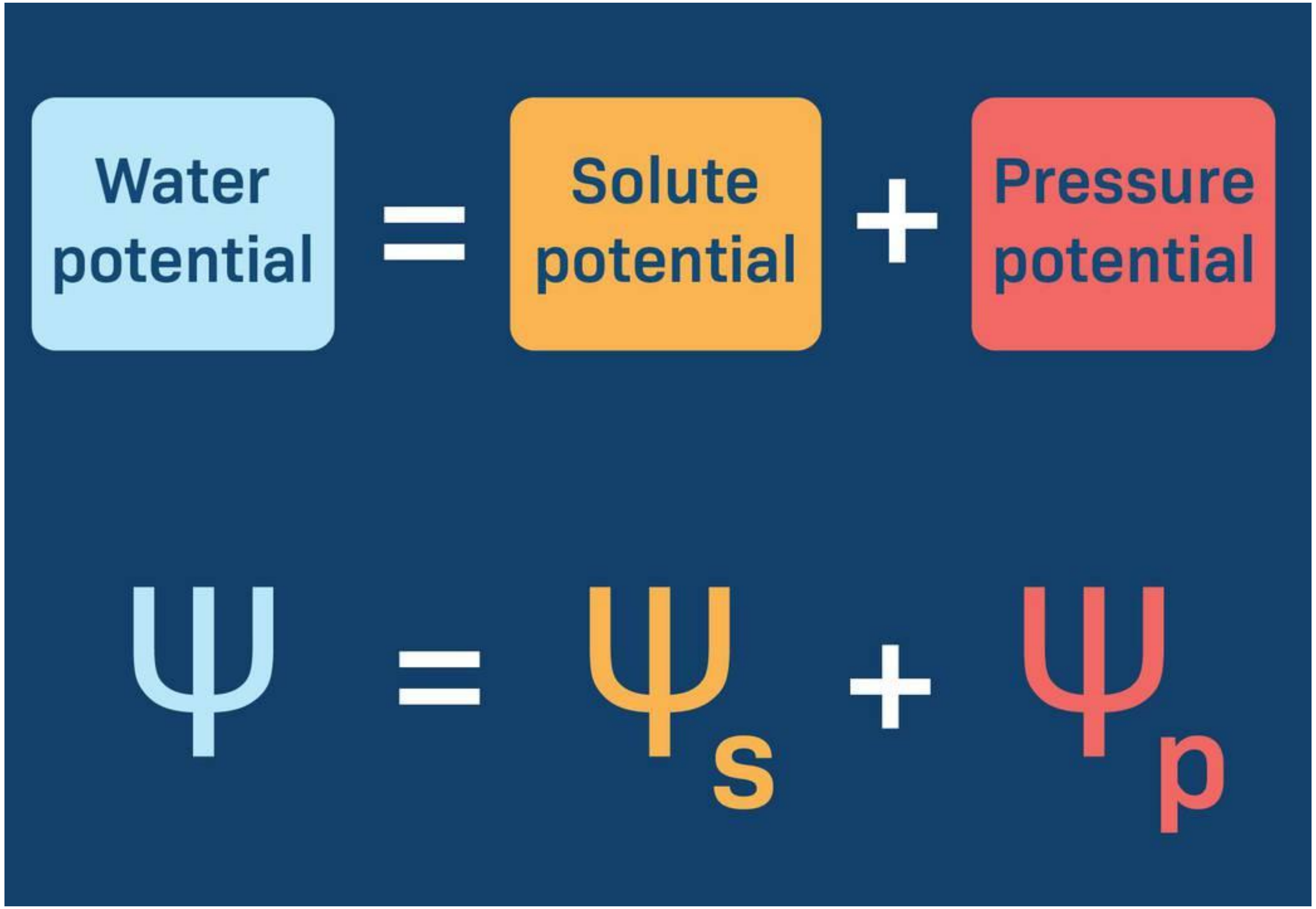
By definition, the water potential of pure water is zero, and any solution that has a water potential less than zero has a tendency to take up water from pure water. Water potential has two major components: **solute potential** and **pressure potential**.

4. Water potential



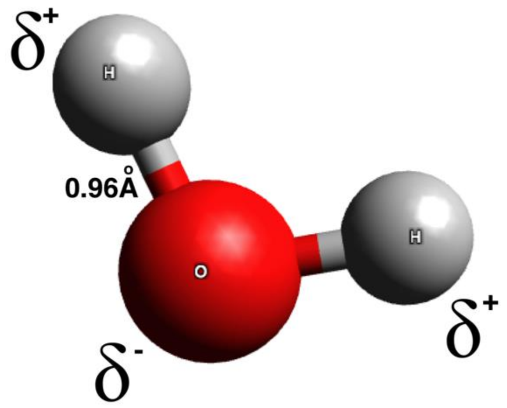
4. Water potential

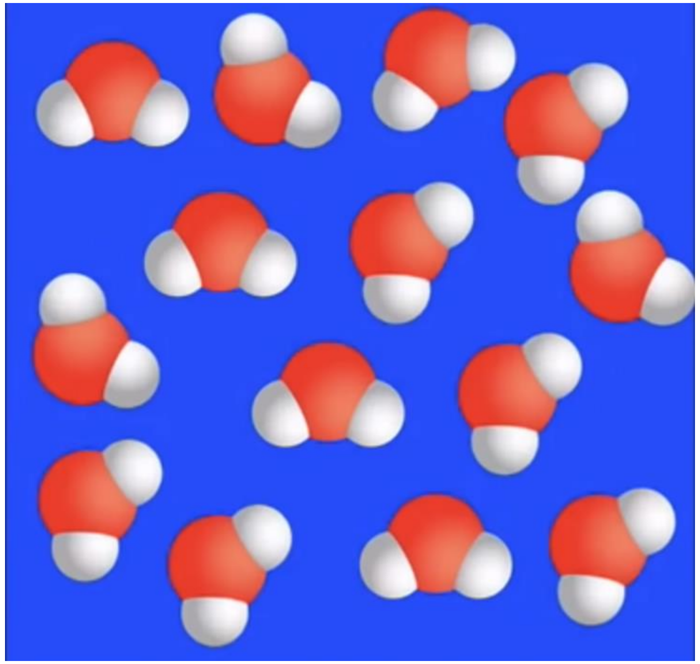
For a single plant cell, its water potential has two components.

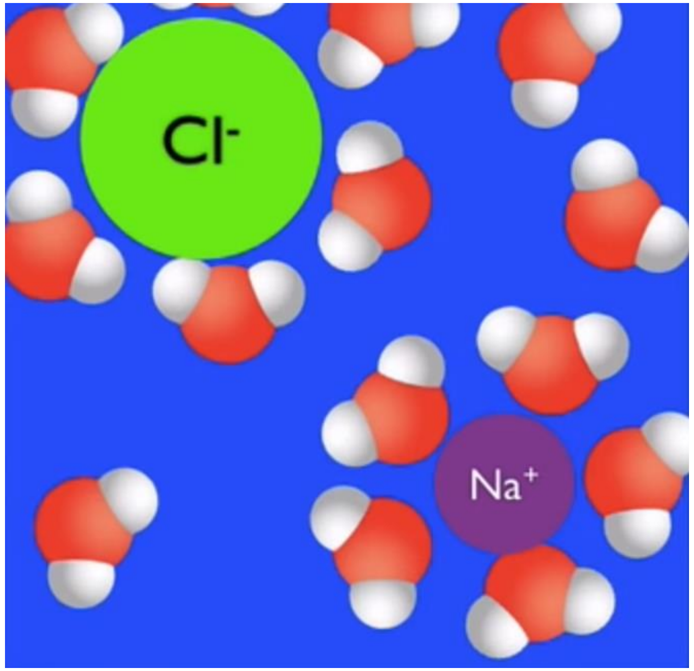


4. Water potential

What does solute potential mean?







0 → negative

4. Water potential

Solute potential (ψ_s), also known as osmotic potential (ψ_π)

It refers to the potential of solute particles that lower the water potential or free energy of water molecules within a solution.

Osmotic potential (π) = -iCRT

i = Van' t Hoff' s factor (It is dimensionless), 中文也称解离系数

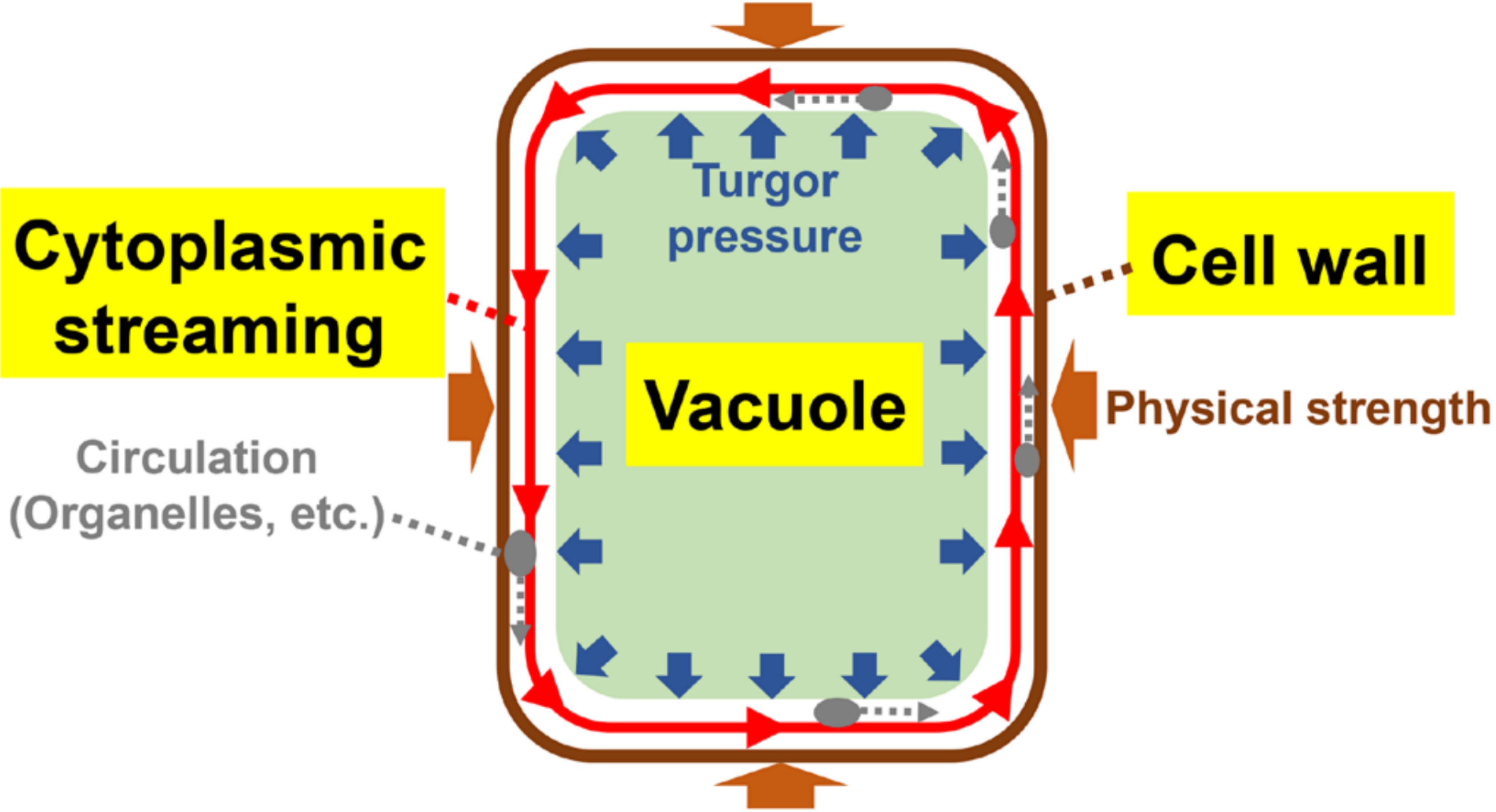
C = Molar concentration in solution, i.e. mol/kg.

R = Gas constant (8.3144598 J·mol^{-1}·K^{-1})

T = Absolute temperature in Kelvin (K)

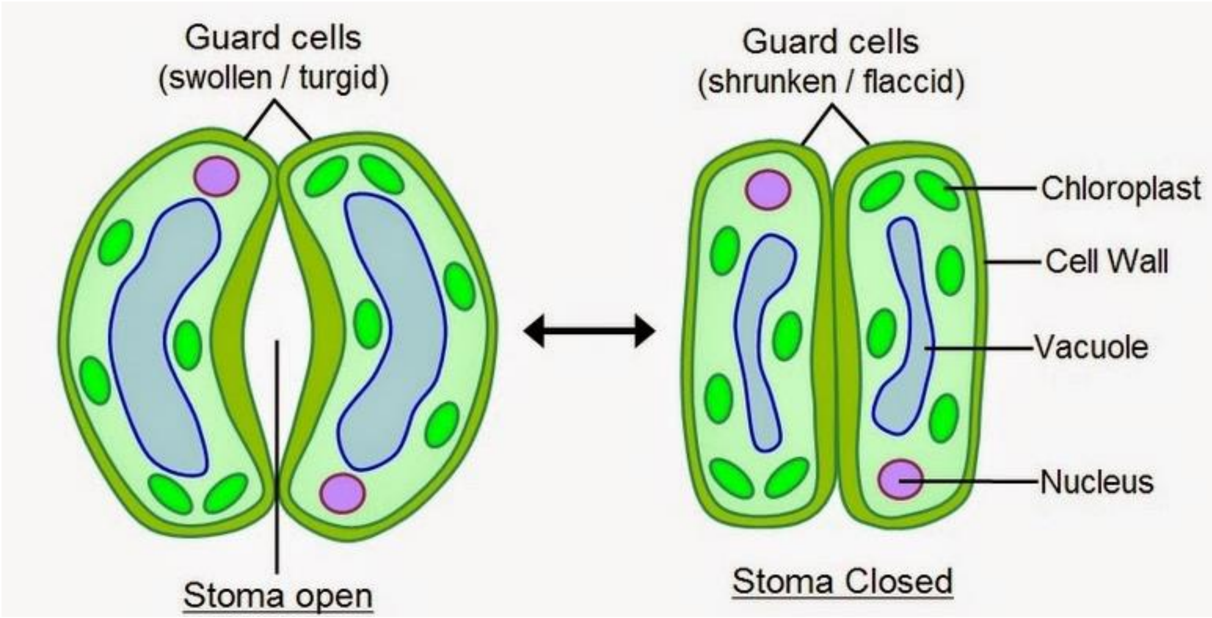
4. Water potential

Pressure potential (ψ_s), is the physical, often positive, pressure exerted by water against plant cell walls (turgor pressure) or negative pressure (tension) in xylem

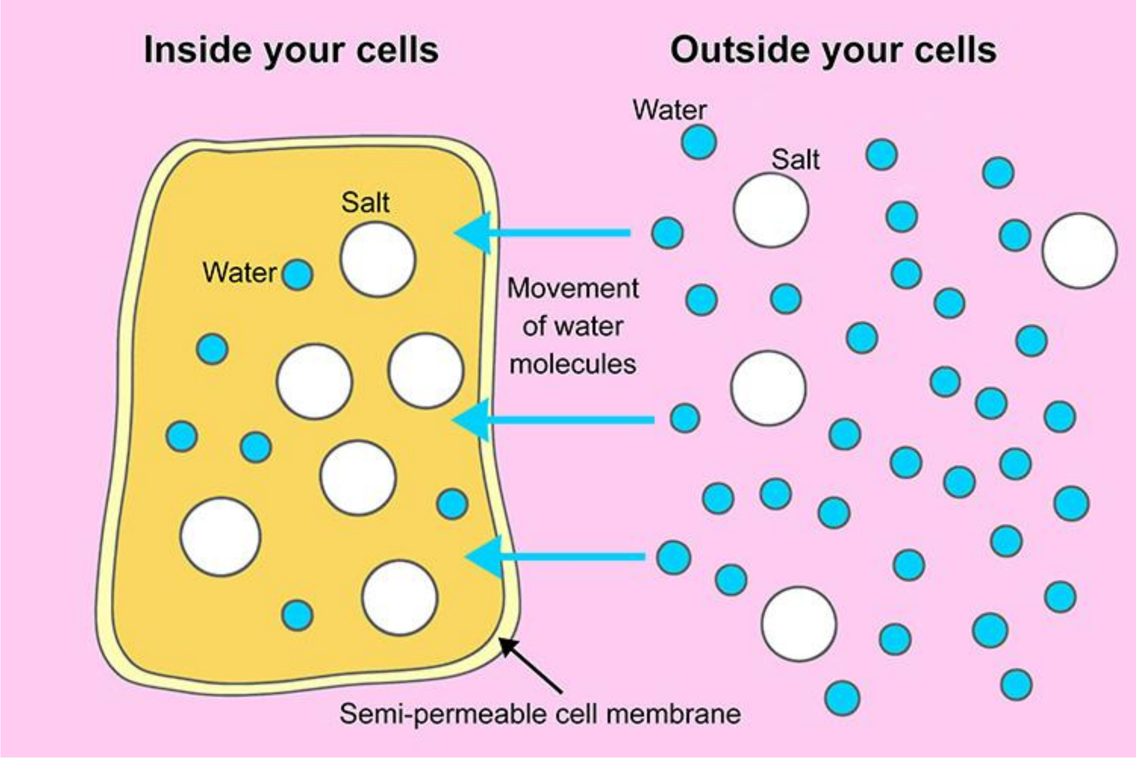


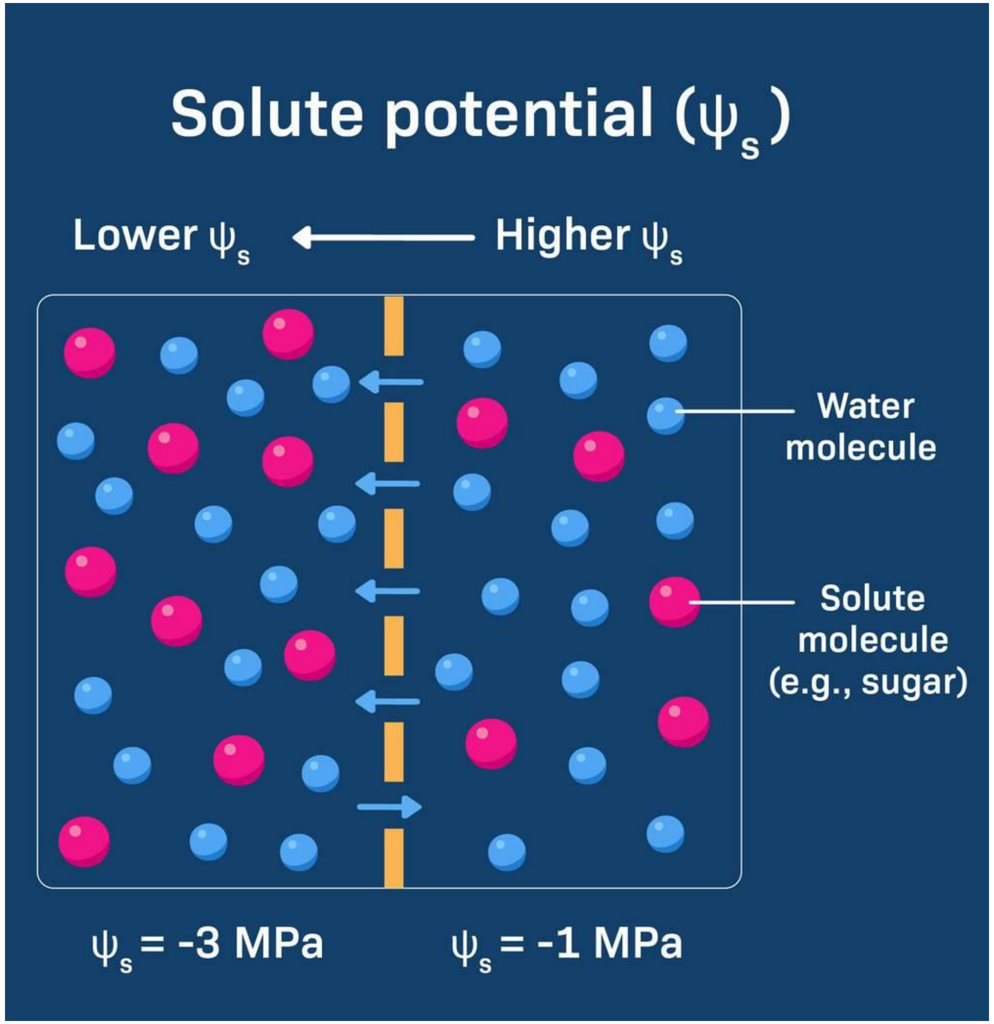
4. Water potential

Turgor pressure



Water Movement by Osmosis Mainly Into or Out of Cells





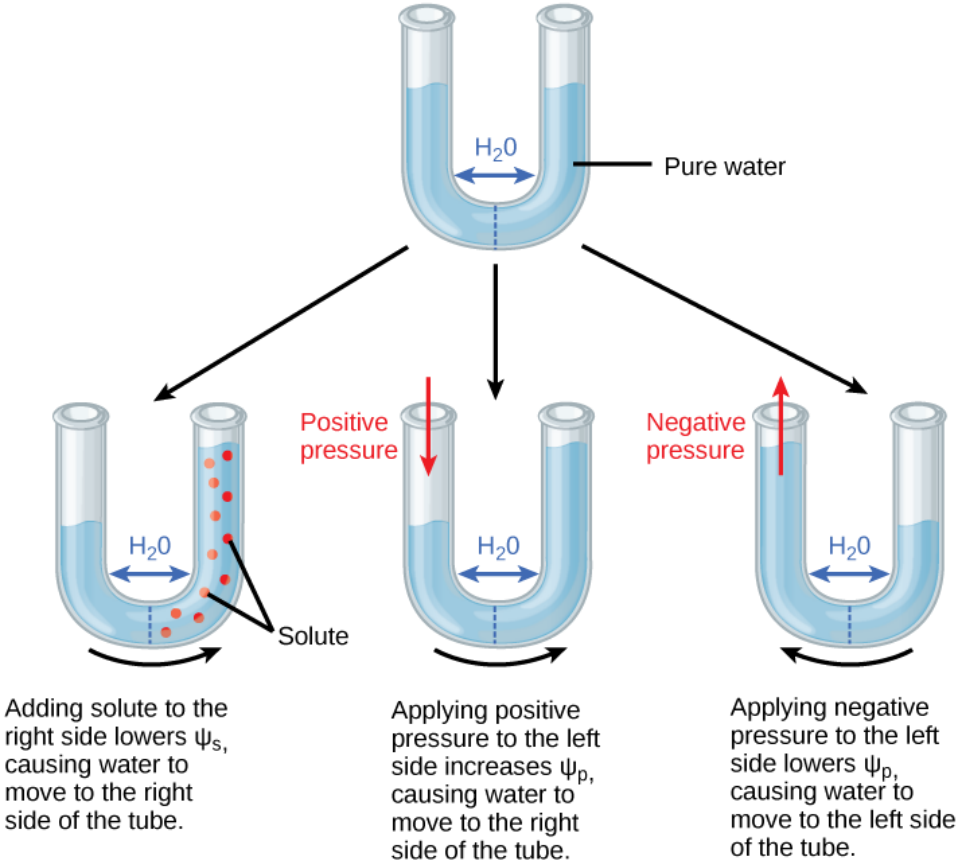
4. Water potential

Question: As we know that water potential represents the chemical potential of water (energy per mol), why the unit of water potential is expressed in pressure?

Potential is the work that a mole of molecules can do.

Question

How to define the "**WORK**" under the water potential framework?



4. Water potential

Question: As we know that water potential represents the chemical potential of water (energy per mol), why the unit of water potential is expressed in pressure?

The chemical potential is not known in absolute terms because the total amount of energy in molecules is not known. Therefore, the work is determined by comparing the chemical potential of the system with a reference potential.

If we define the chemical potential of the system to be measured as μ_w and the chemical potential of the reference system as μ_0, (μ_w - μ_0) is the comparison we wish to make.

$$\psi_w = \frac{\mu_w - \mu_0}{\bar{V}_w}$$

Extension

Pressure is typically expressed in megapascals (MPa). 1 MPa = 10^6 pascals = 10^6 newtons m^{-2} = 1 joule m^{-3} = 10 bars = 9.87 atmospheres.

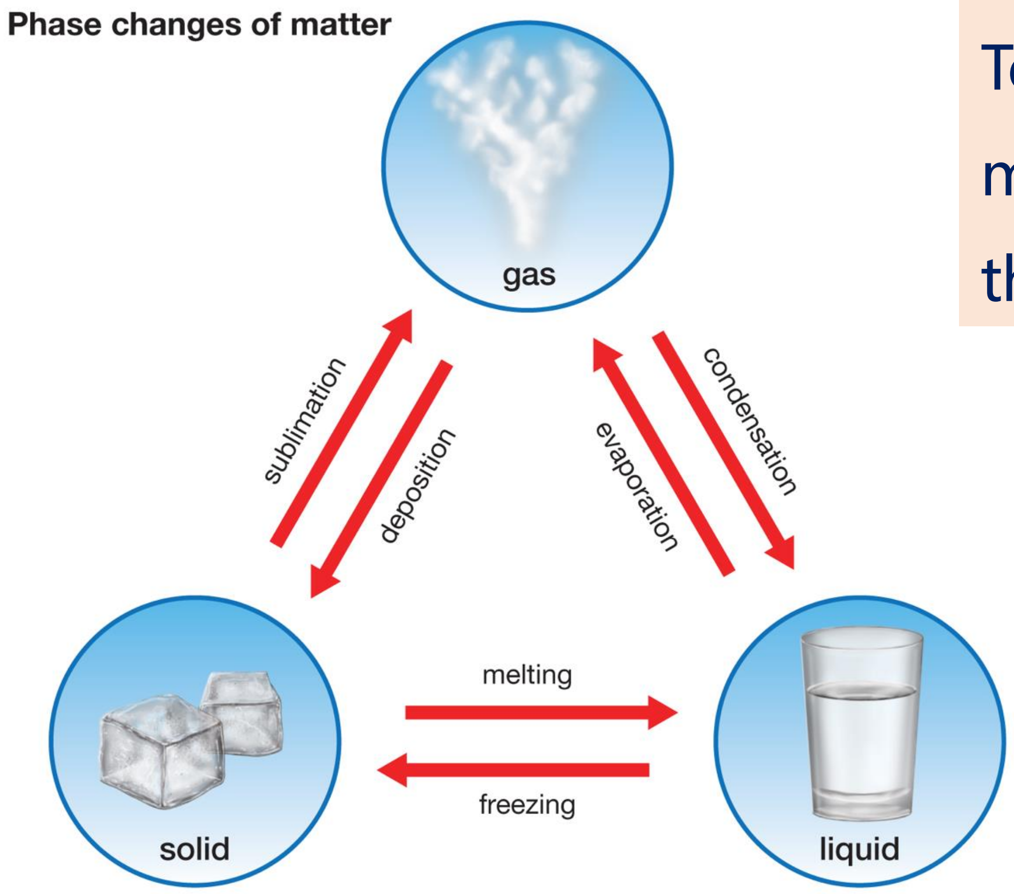
Advantages in using water potential to express water status of plants

- Water potential has the advantage that the water status is compared to a physically defined reference rather than a biological one, and the physical reference allows the chemical potential to be precisely reproduced at any time or place.
- The chemical potential has the further advantage that the forces moving water through the soil, plant and atmosphere can be measured.

How do you measure water potential?

Measuring water potential (Brief introduction)

Principles of the methods



To measure water potential is, actually, to measure the chemical potential of water in the system.

Measuring water potential (Brief introduction)

Principles of the methods

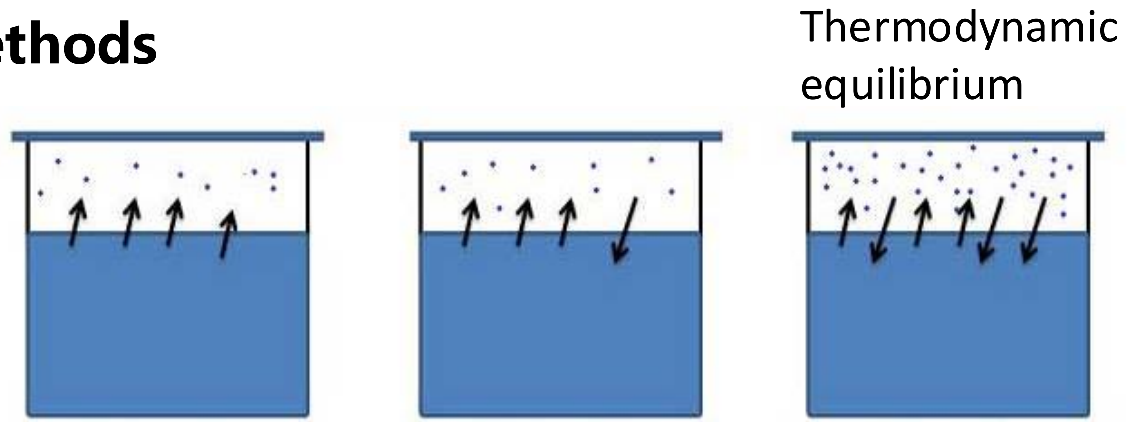
From a physical perspective, the work with liquid water can be measured by holding the volume constant and measuring the change in pressure or by holding the pressure constant and measuring the change in volume. Obviously, the holding the volume constant is easier.

$$\begin{aligned}\mu_w - \mu_0 &= \int P \, dV \\ &= \bar{V}_w \int_0^P dP \\ &= \bar{V}_w (P - 0)\end{aligned}$$

$$\psi_w = \frac{\mu_w - \mu_0}{\bar{V}_w} = P$$

Measuring water potential (Brief introduction)

Principles of the methods



Measuring work with vapor pressure follows a similar procedure. The pressures are applied to water vapor in the gas phase, and, of course, in this case, the volume of water is no longer constant.

$$v = RT/e$$

$$\mu_w - \mu_0 = \int e\,dv$$

$$= RT\int_{e_0}^{e_w}\frac{de}{e}$$

$$= RT\ln\frac{e_w}{e_0}$$

$$\psi_w = \frac{RT}{\bar{V}_w}\ln\frac{e_w}{e_0}$$

Measuring water potential (Brief introduction)

Critical thinking

How does ψ_w respond to temperature changes? Why?

$$\psi_w = \frac{\mu_w - \mu_0}{\bar{V}_w} = P$$

$$\psi_w = \frac{RT}{\bar{V}_w} \ln \frac{e_w}{e_0}$$

μ_w & μ_0: isothermal nature of measurement

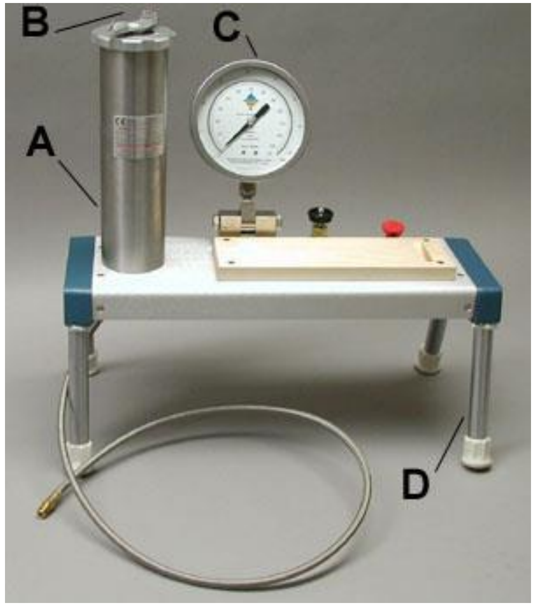
e_w & e_0: isothermal nature of measurement

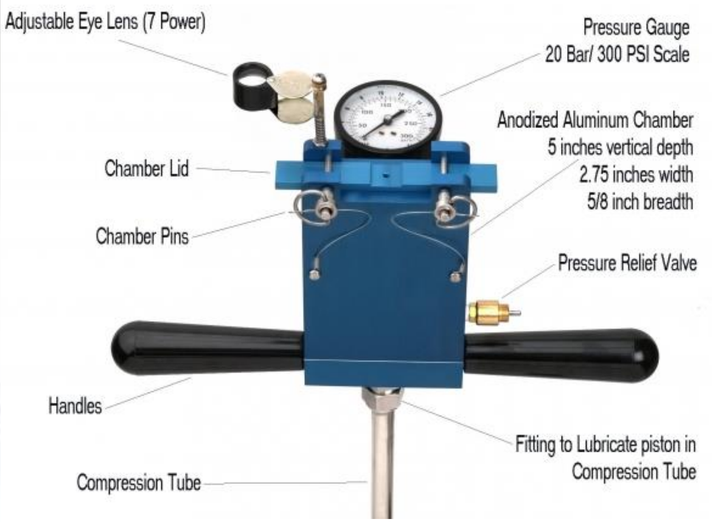
Mostly ***T***

Slightly **V_w: decreases, then increases at lower temperature**

Measuring water potential (Brief introduction)

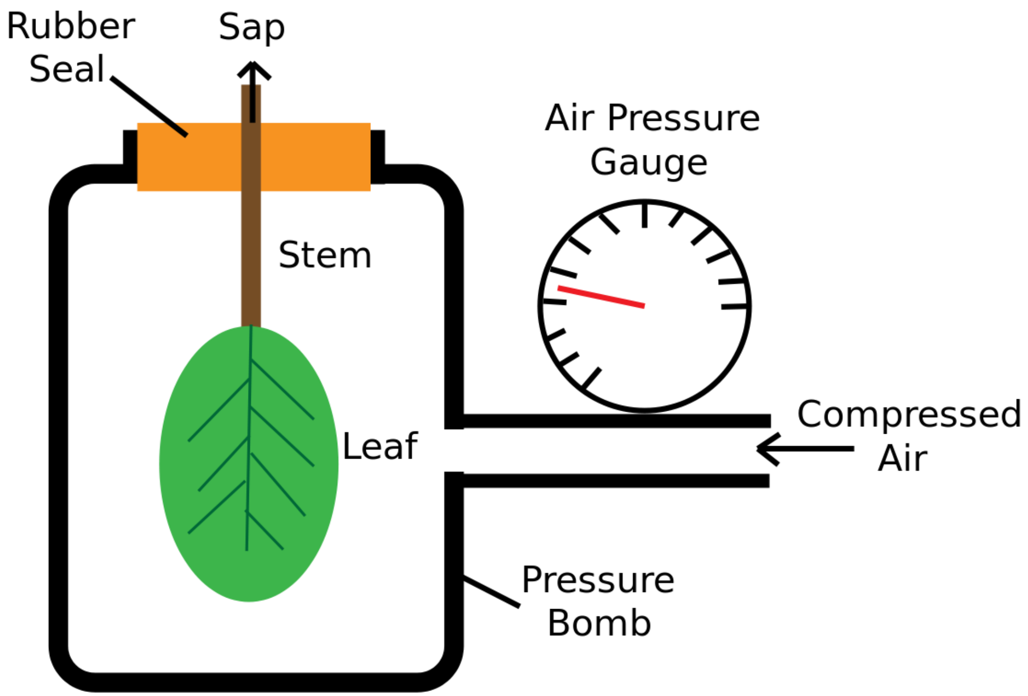
Pressure bomb (chamber)

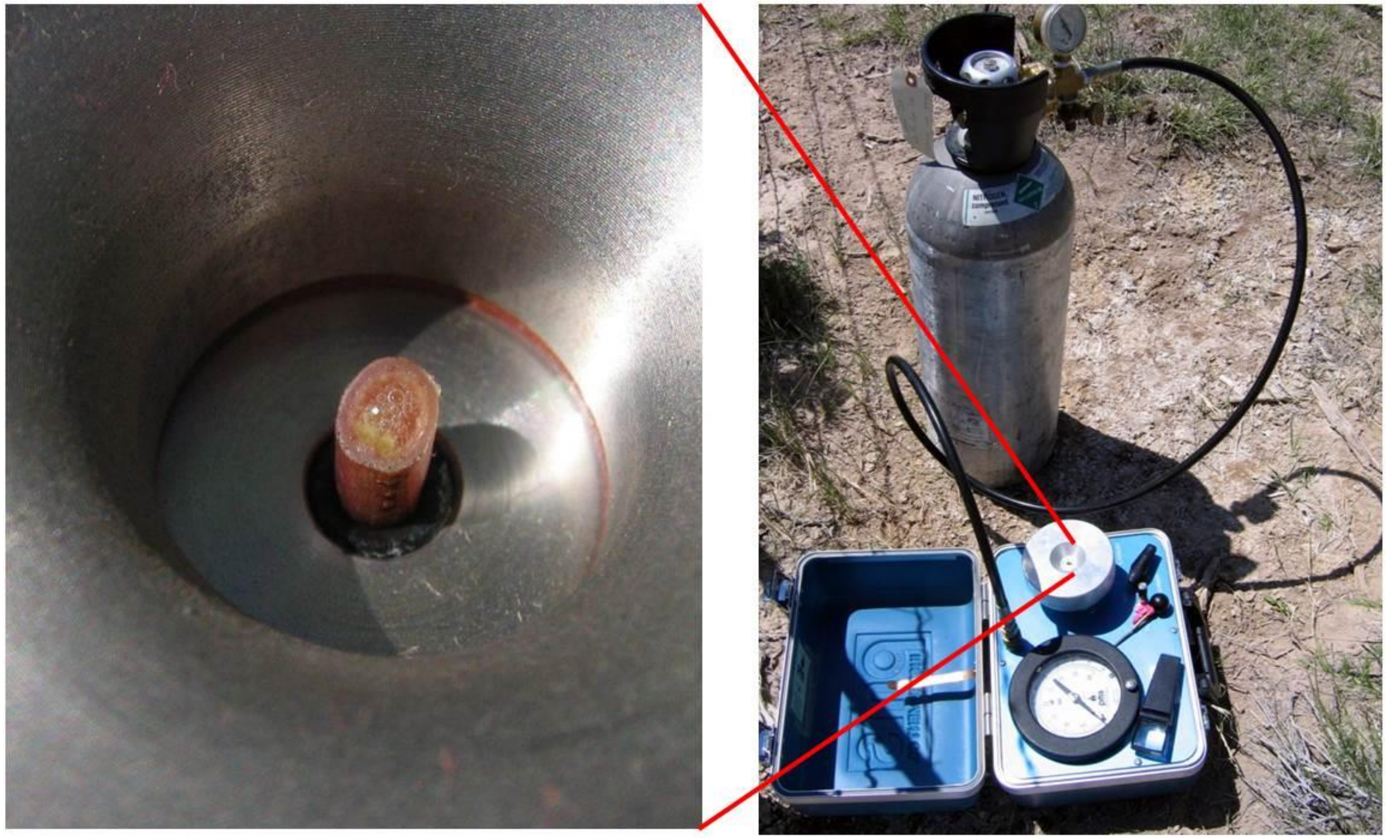




Measuring water potential (Brief introduction)

Pressure bomb (chamber)



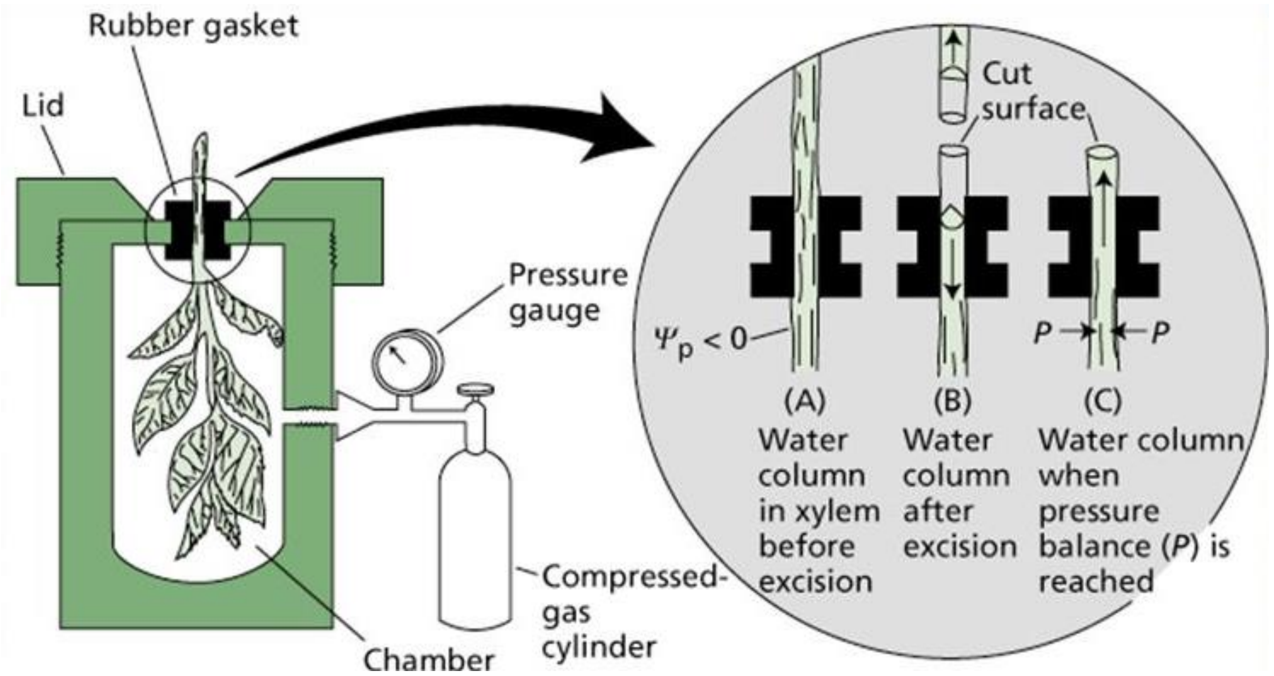


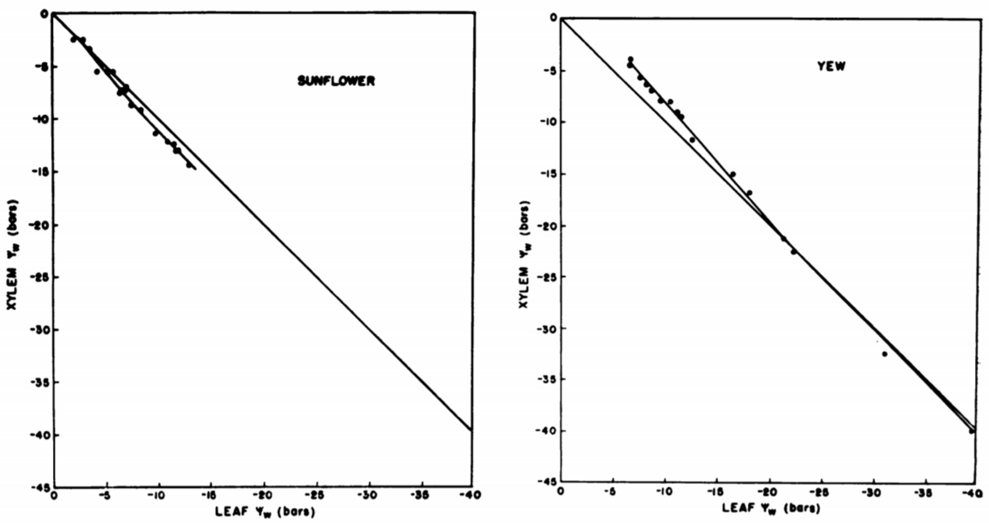
Measuring water potential (Brief introduction)

Pressure bomb (chamber)

Question

Pressure chamber actually estimates the negative pressure inside xylem, and therefore, the question is why we use the values from the pressure chamber to represent the water potential of tissues?





Boyer 1976 Plant Physiology

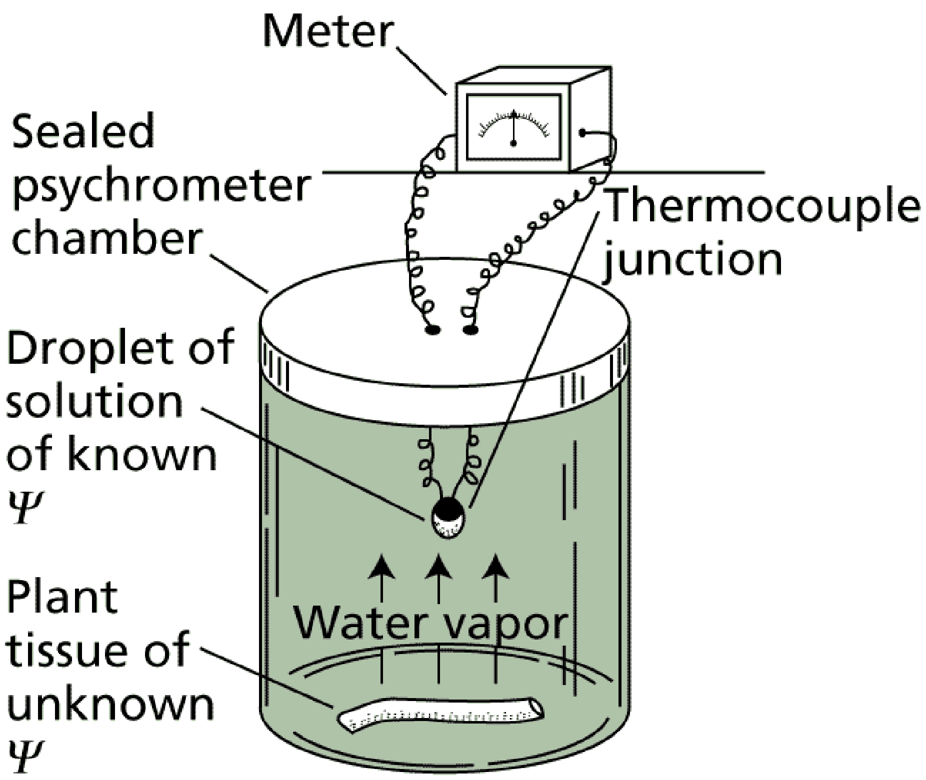
Measuring water potential (Brief introduction)

Thermocouple psychrometry

Dew point psychrometer

Measuring water potential (Brief introduction)

Thermocouple psychrometry



Thermocouples

Seebeck effect: a temperature difference between two dissimilar electrical conductors or semiconductors produces a voltage difference between the two substances. 温差生电

Peltier effect: the presence of heating or cooling at an electrified junction of two different conductors. 通电生冷/生热

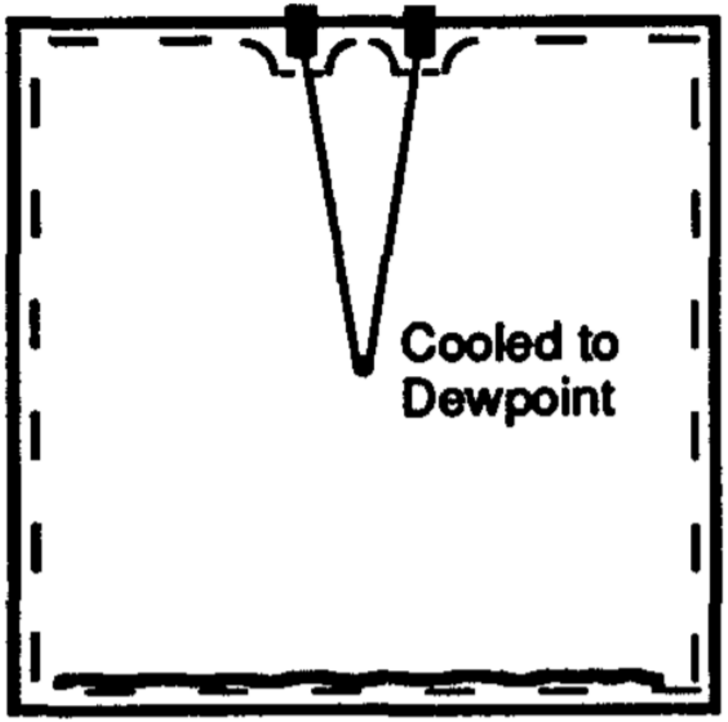
Thomas effect: heating or cooling of a current-carrying conductor with a temperature gradient.

Thermocouple psychrometry is the most widely used method of measuring plant water status and probably is the most versatile.

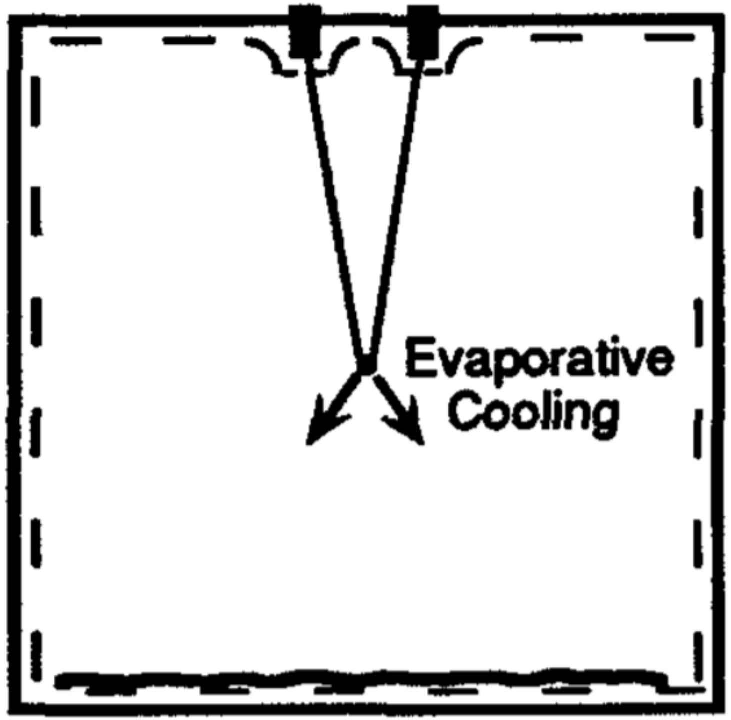
Measuring water potential (Brief introduction)

Thermocouple psychrometry

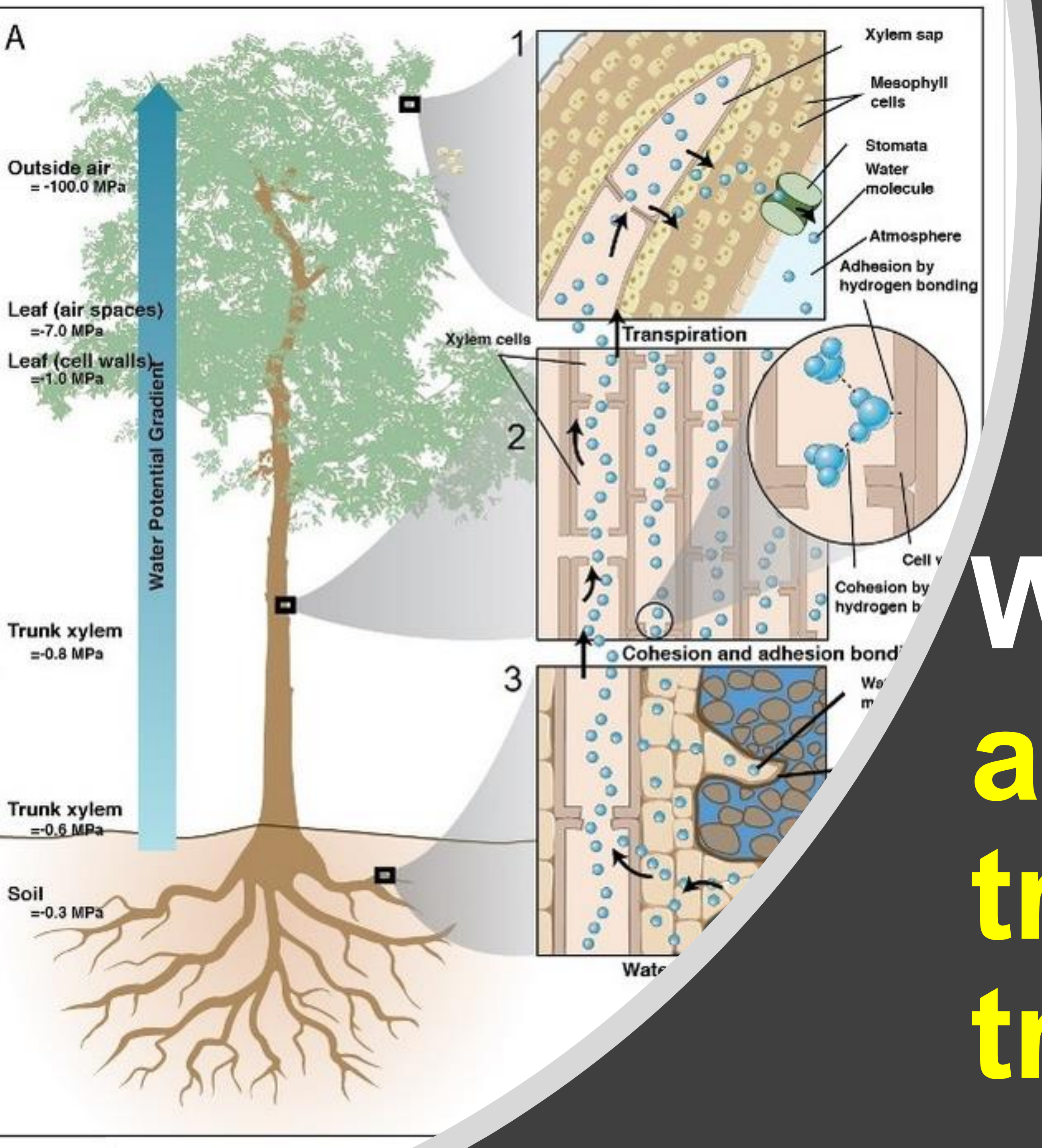
Isopiestic psychrometer



Dew point psychrometer



Peltier psychrometer



Water **absorption, transportation & transpiration**

Availability of water for plants:
-- function of water regime and soil characteristics

Water regime

Precipitation: Total amount rain (l m^{-2})

Annual precipitation (mm / year):
As lower is more unpredictable results

Frequency:
Number of raining days /year

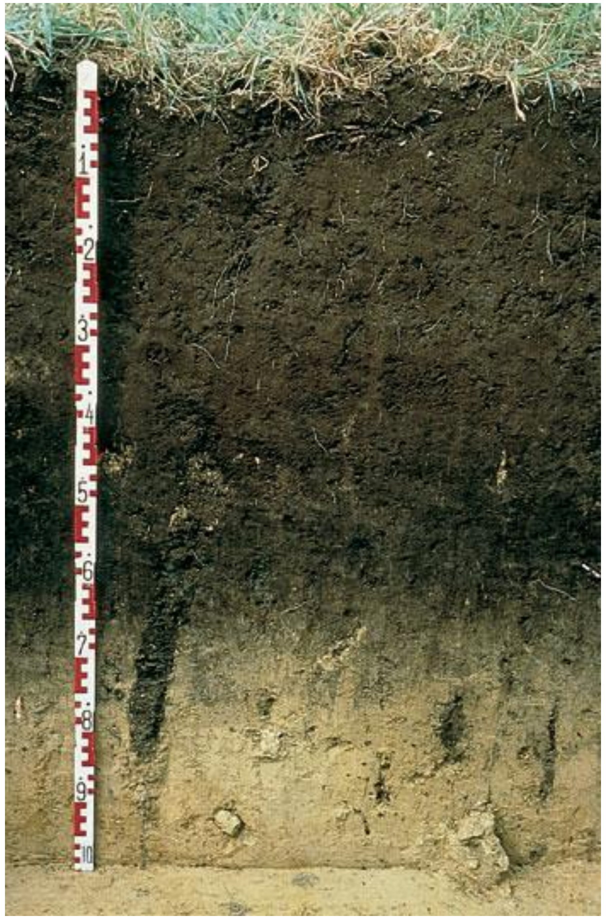
Distribution all over the year:
Coincidence with growth season (thermal- irradiance optimum (Temperate climates) or with cold –radiation limited growth seasons (Mediterranean).

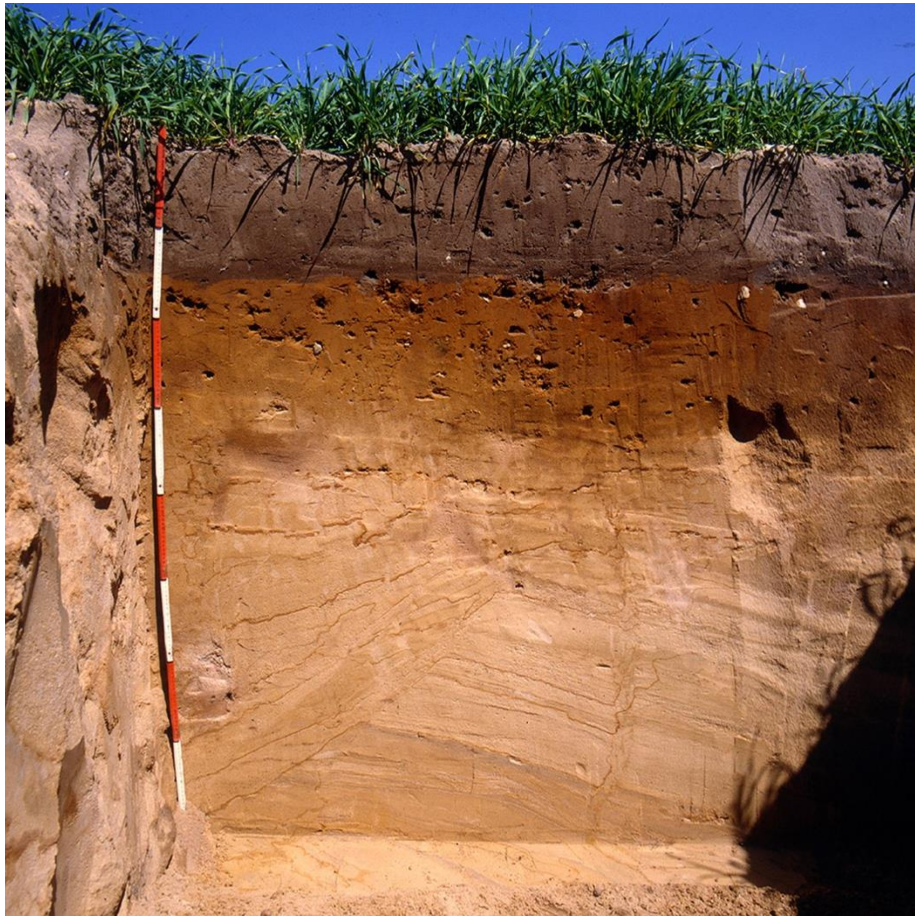
Intensity:
Amount of rain by time unit (mm/hour). **Optimum:** 1 mm/hour.
Higher: Risk of lost of water and erosion.

Water in soil

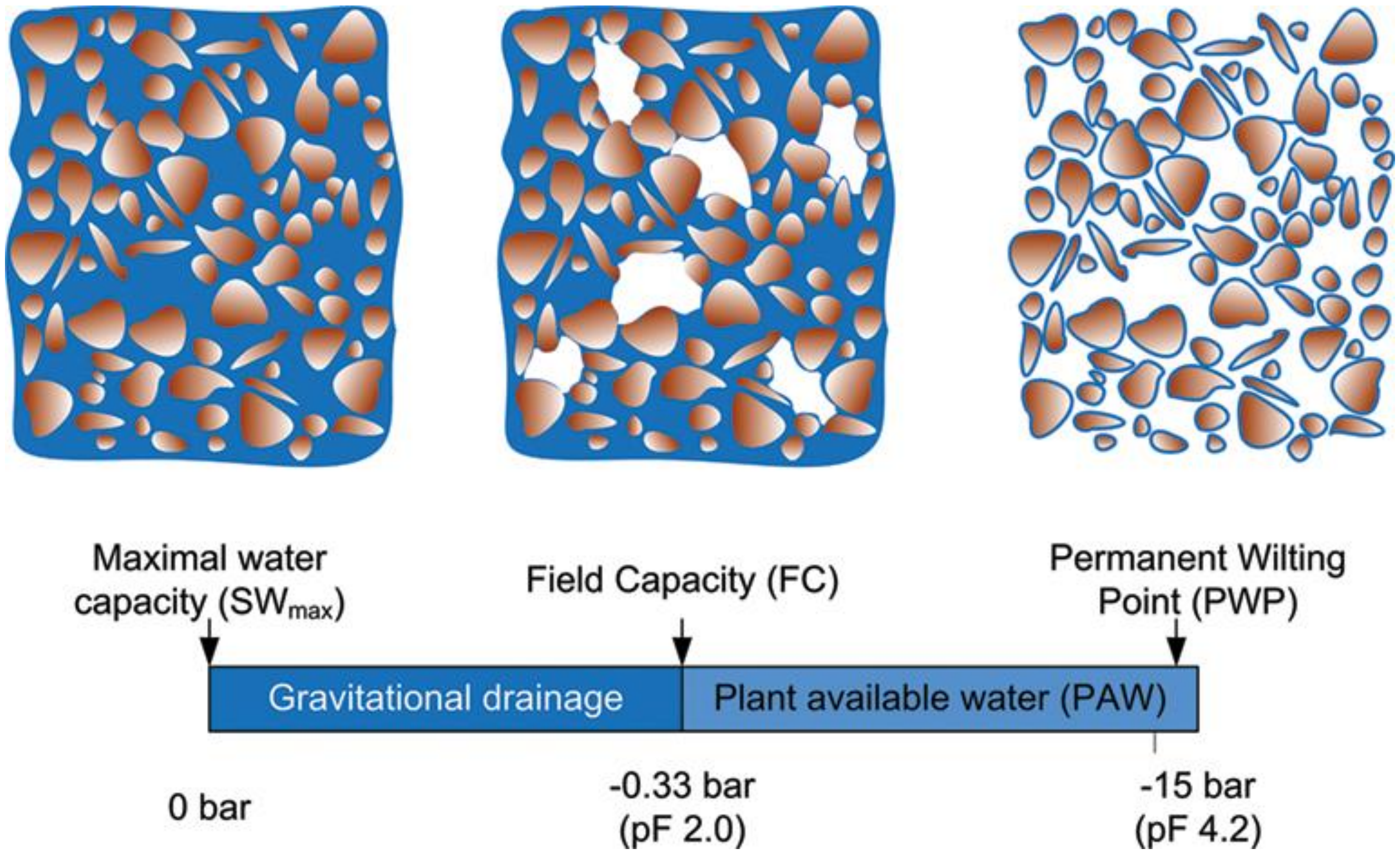
Important: Soil depth / stone volume / Porosity

Organic matter **always improve water storing capacity of the soil**



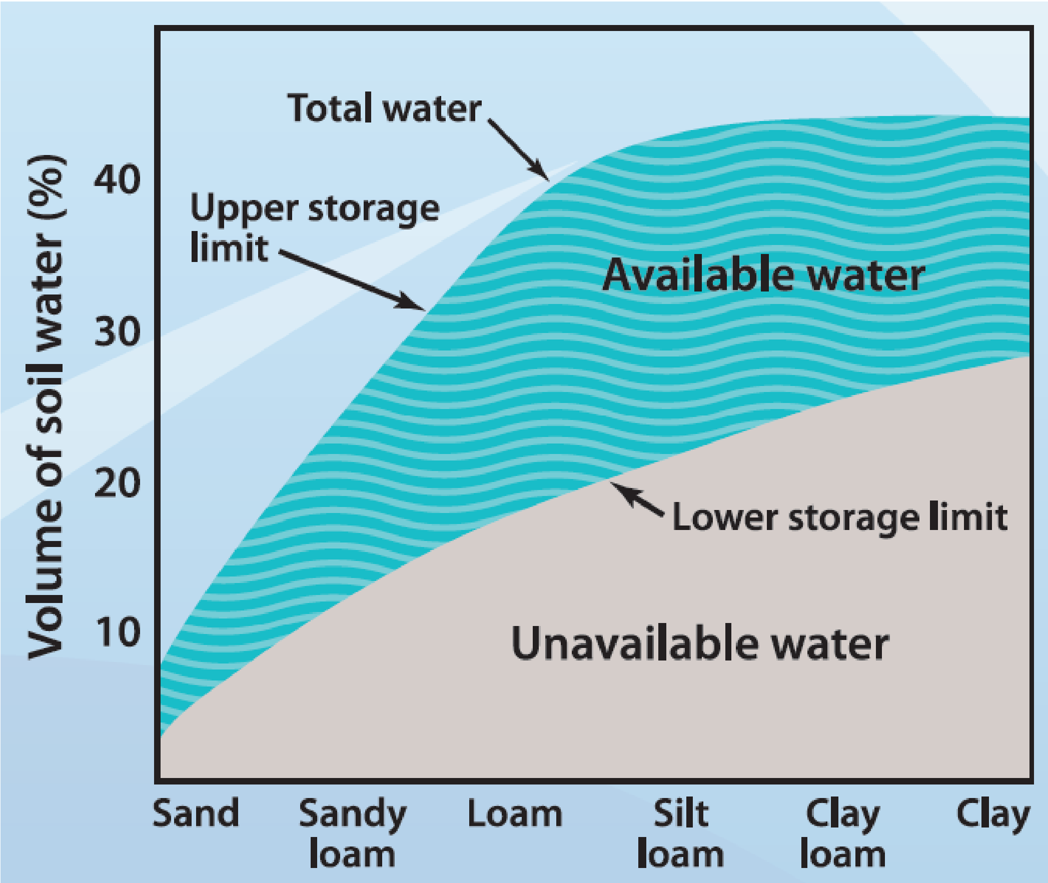


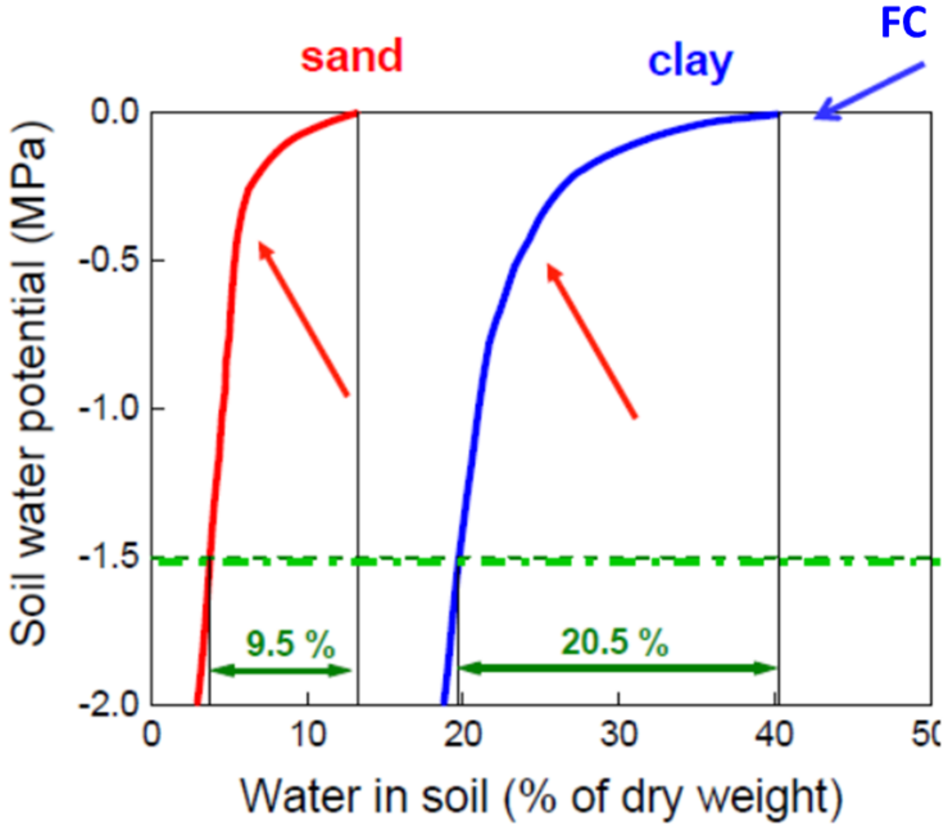
Water in soil



Because of storage effects within the soil pores, the dynamics of soil moisture posses a memory that is often considerably longer than the integral timescale of many atmospheric processes.

Water in soil



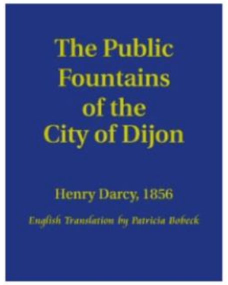


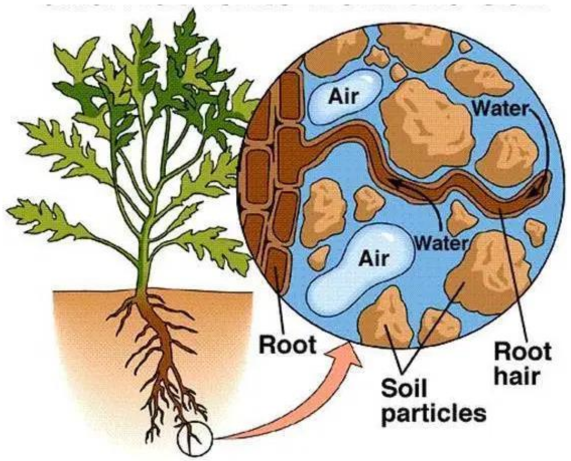
Fluxes and water flow in soil

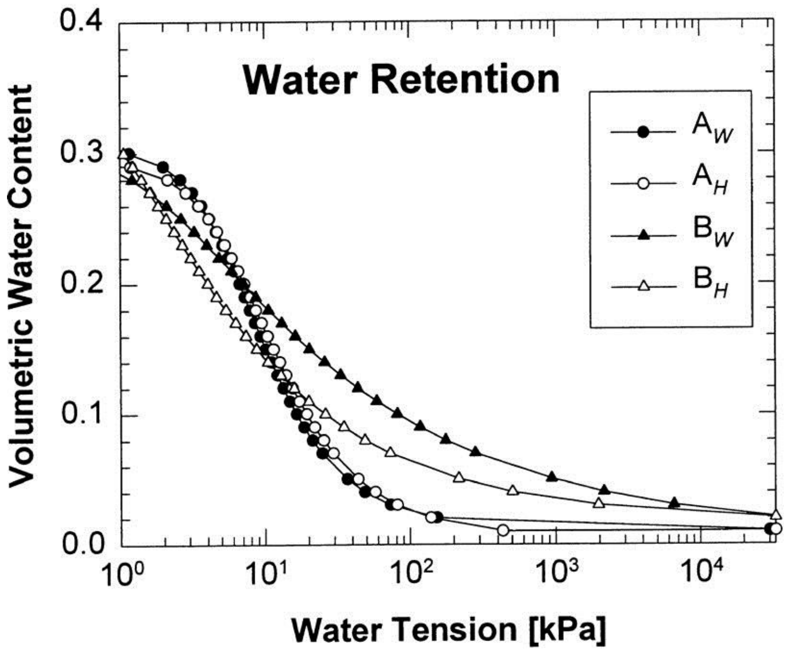
$$q_w = -K(\theta)\frac{dH}{dL}$$

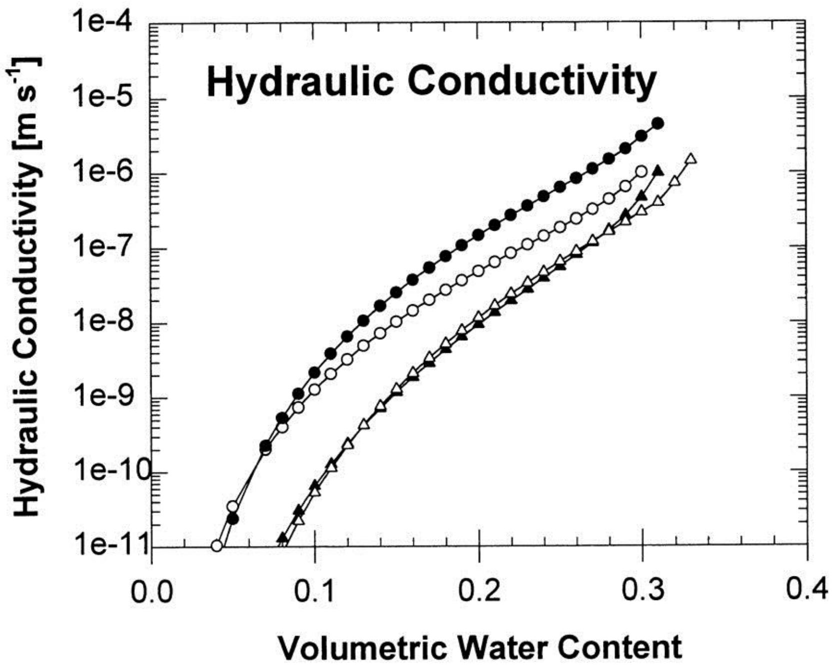
Hydraulic conductivity

Energy gradients – that themselves vary with soil moisture





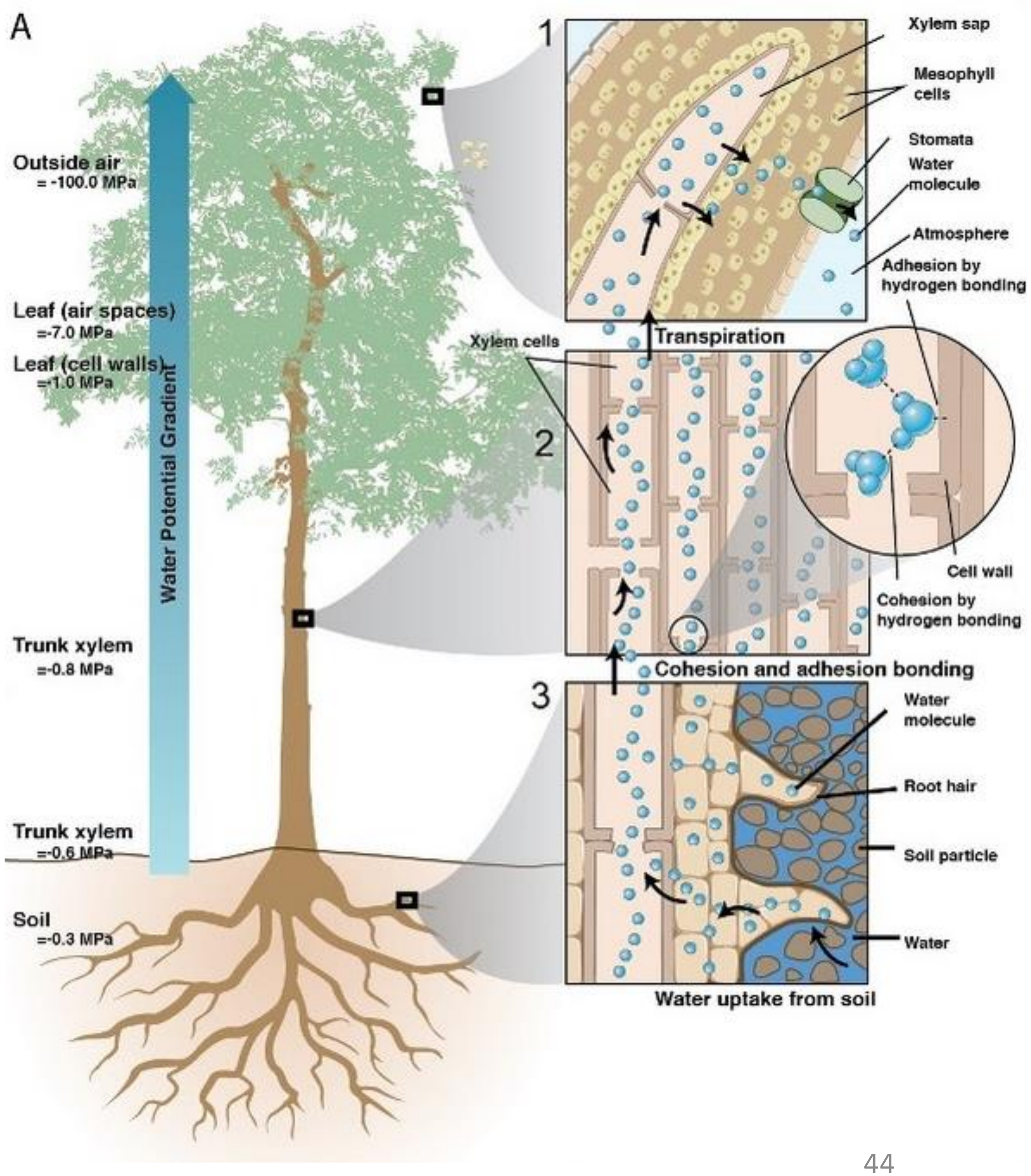




Two fundamental Hydraulic functions Characterizing soil type

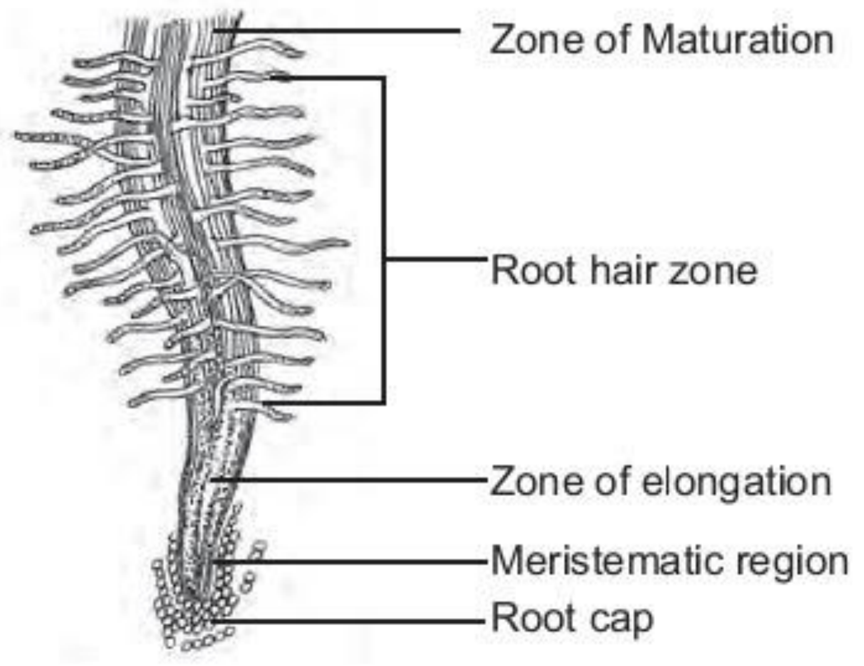
Outline

- Water status of plants
- Availability of water
- **Water uptake from soil by roots**
- **Water escapes from plants**
- **Water transport through plants**
- **Water Use & Stress**

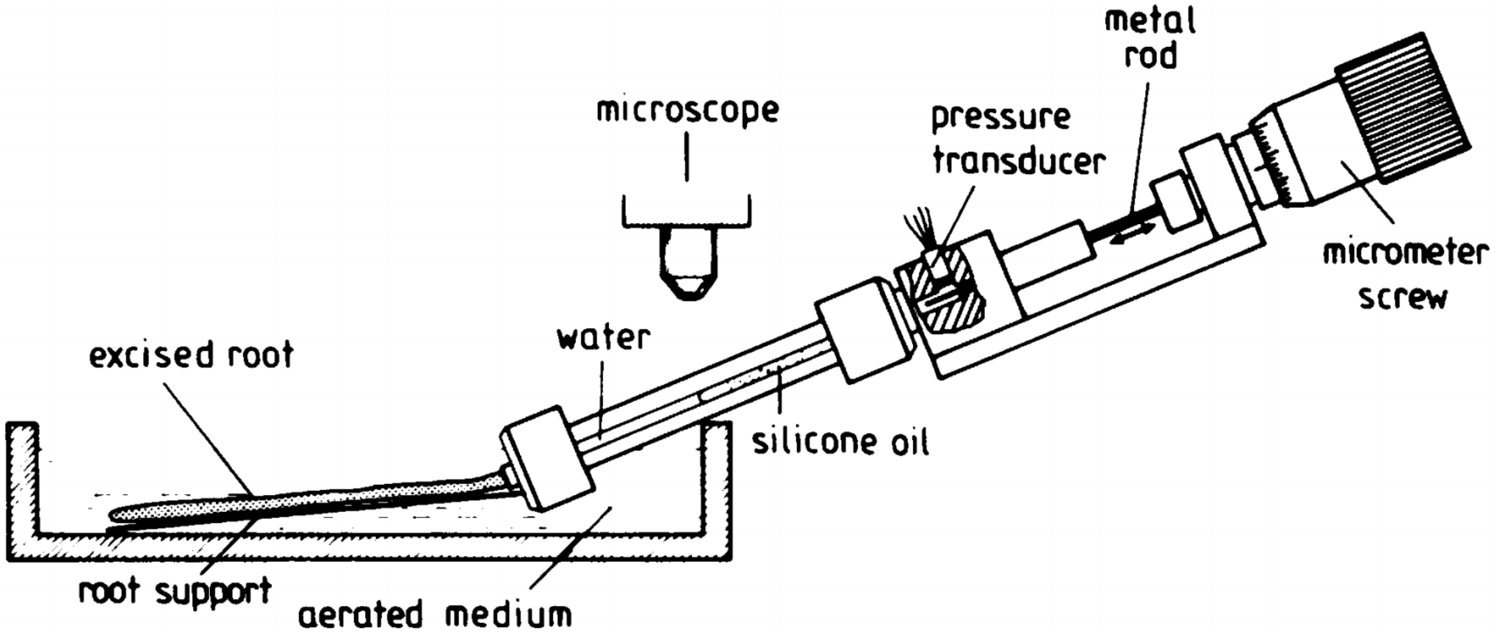


Water uptake from soil by roots

Which part of root uptakes water from soil?



Regions of the Root

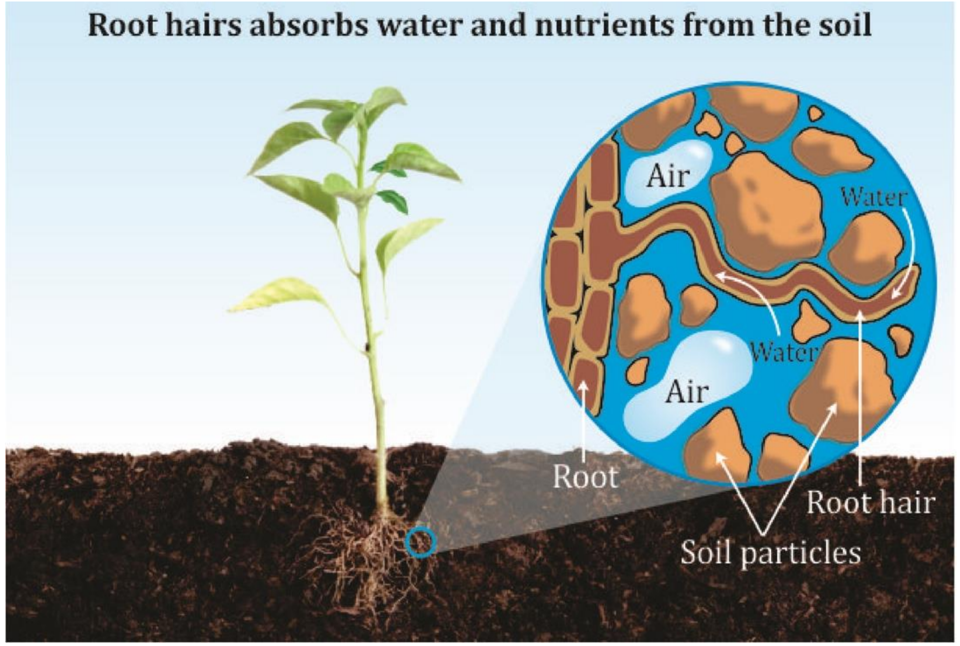


Water uptake from soil by roots

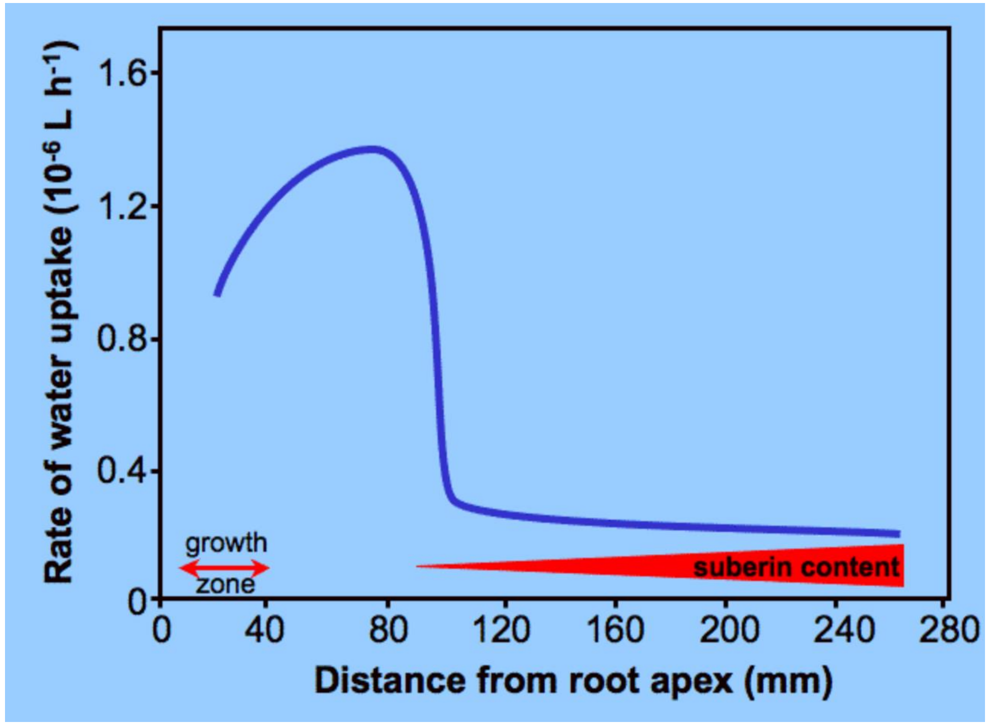
What are the advantages of transplanting with soil attached?

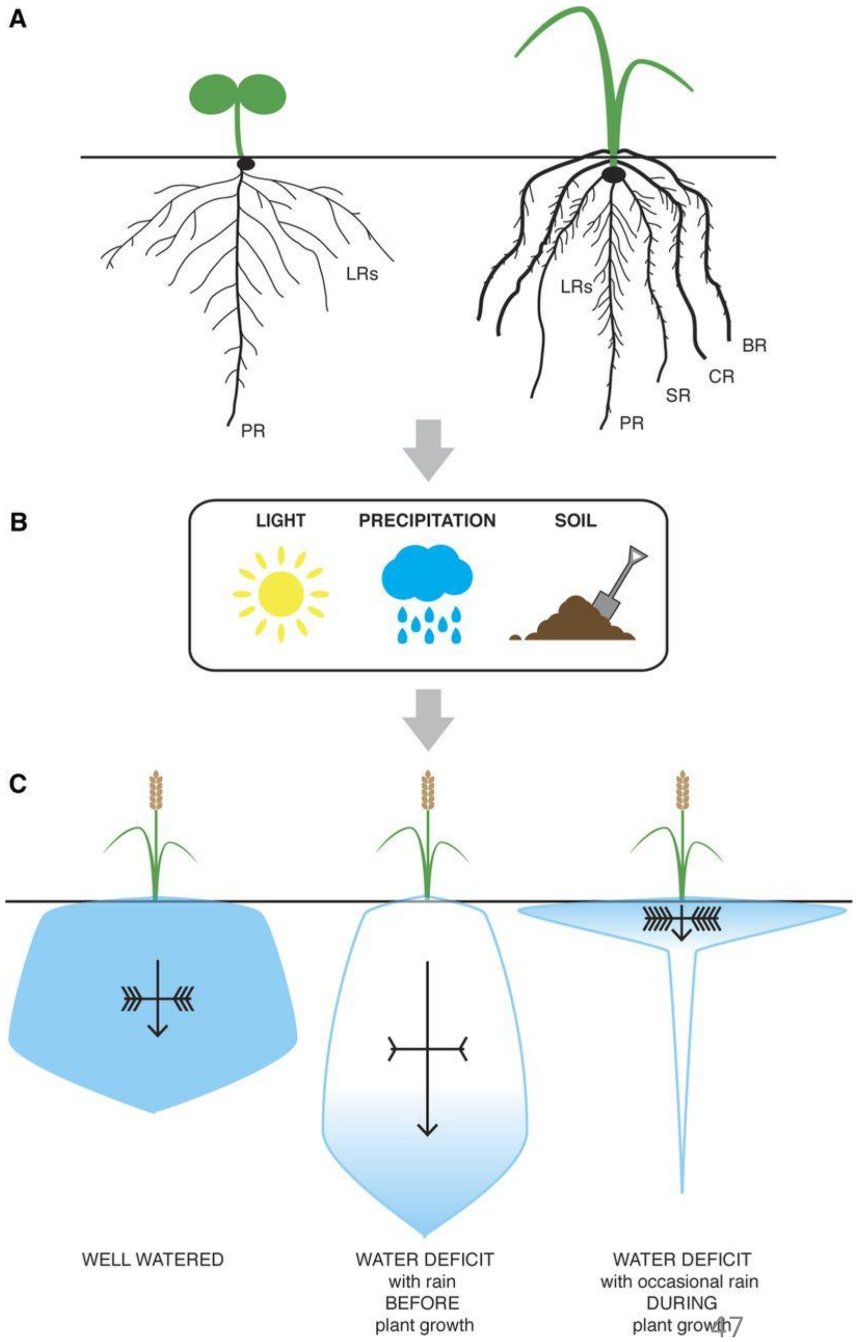
Reasons why the root hair zone has the greatest water (nutrients) absorption capacity:

1. The vascular tissues are well developed, resulting in low resistance to water transport.
2. Root hairs increase the surface area for water absorption.
3. The outer wall of root hair cells is rich in pectic substances, exhibiting strong adhesiveness and high hydrophilicity.
4. Root hairs are slender and can penetrate into soil capillaries.
5. In the meristematic and elongation zones, the cytoplasm is dense and the vascular tissues are underdeveloped or absent, leading to greater resistance to water movement.



Water uptake from soil by roots

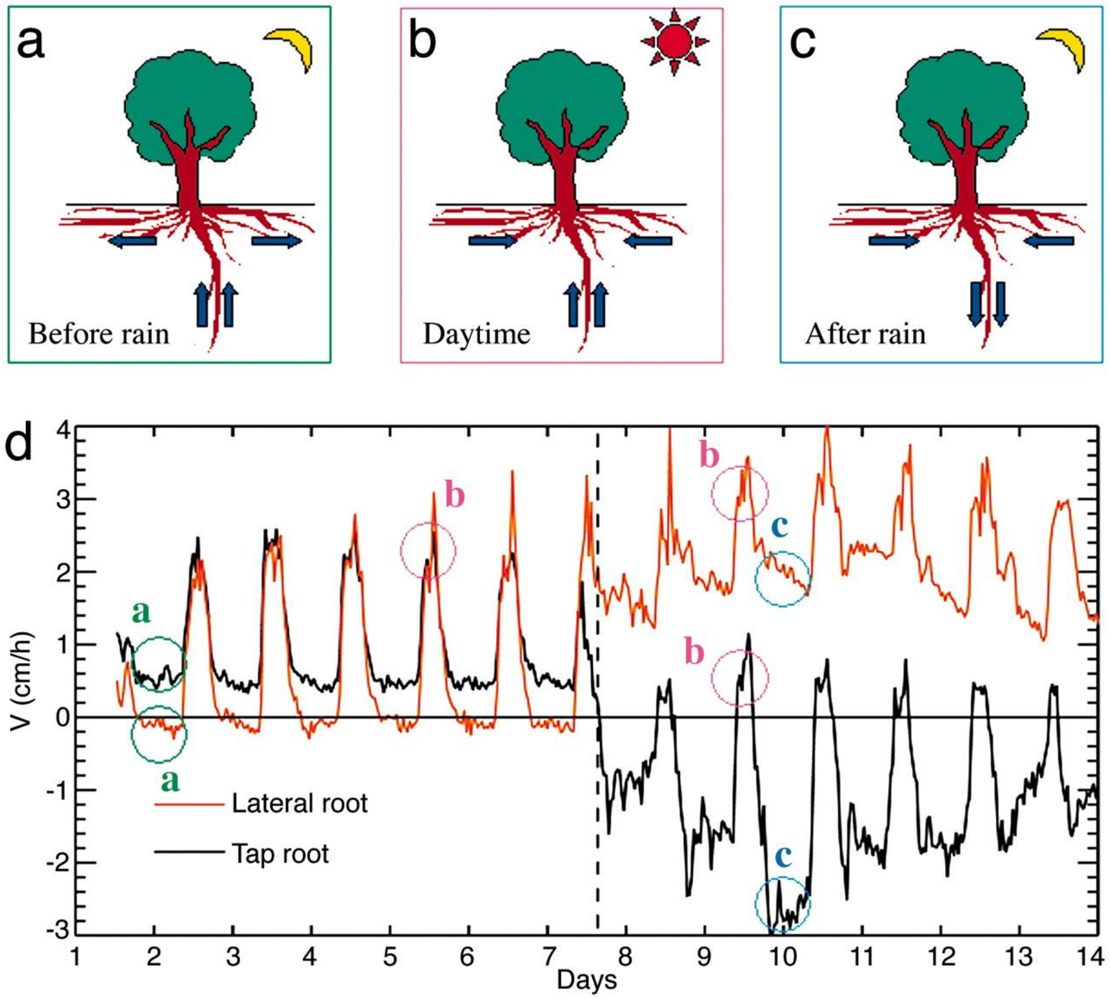


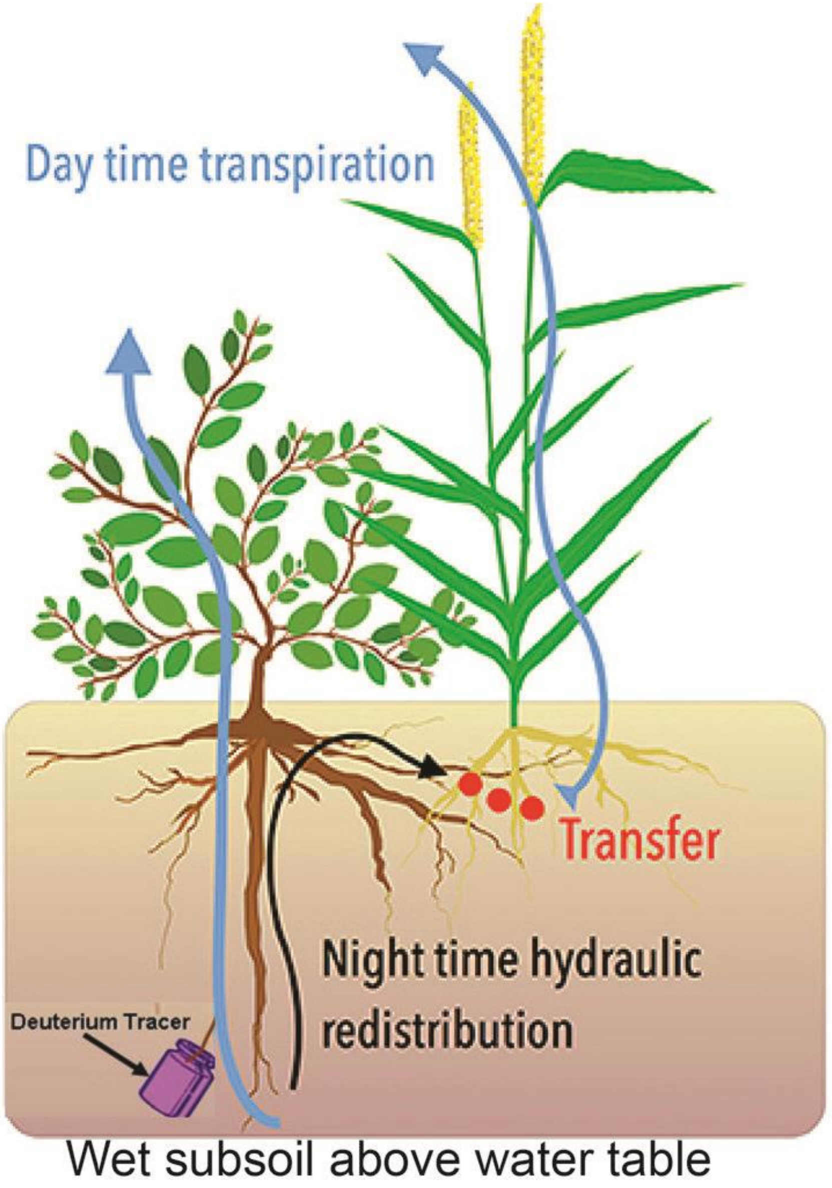


- Water enters the root most readily near the roots tip rather than mature region of the root.
- Water absorption area shaped dramatically by soil water conditions.
- What are advantages that mature regions of the root decline permeable to water?

Water uptake from soil by roots

Hydraulic redistribution

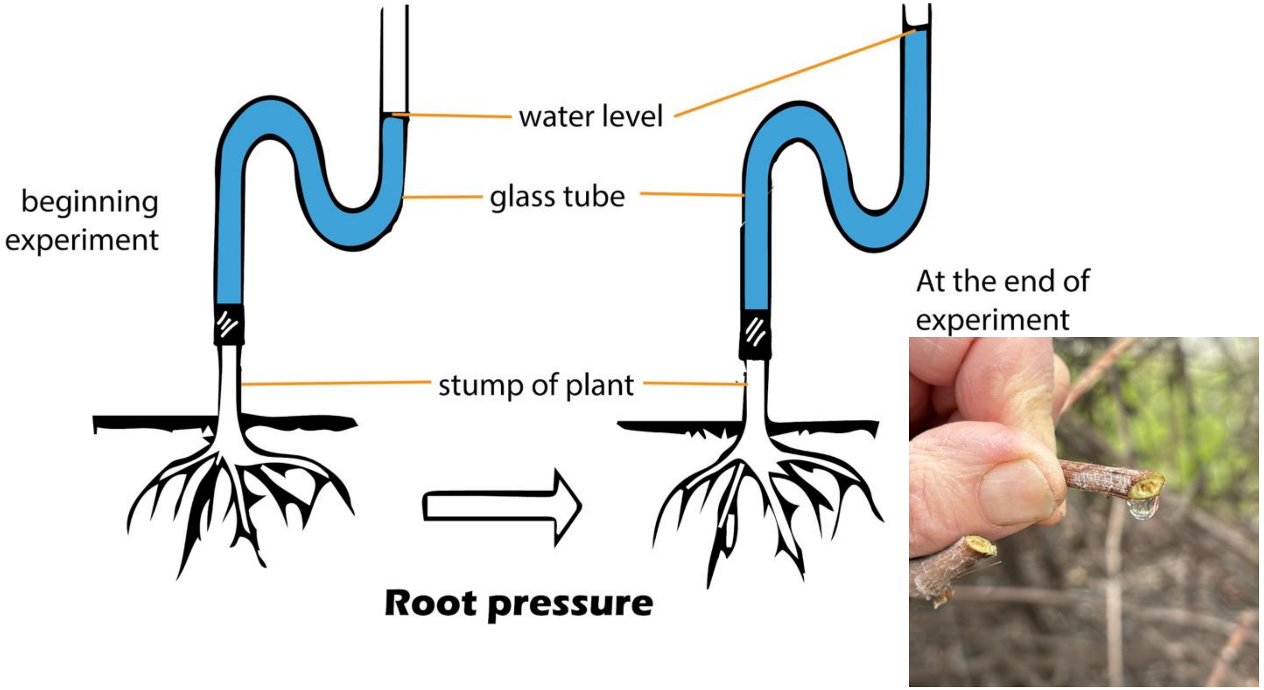




Water uptake from soil by roots

Driving Forces of Water Absorption by Roots

Active absorption, water uptake driven by **root pressure**. The root pressure generated by the physiological activity of the root system that pushes xylem sap upward from the root. In most plants, root pressure is approximately 0.1 MPa.

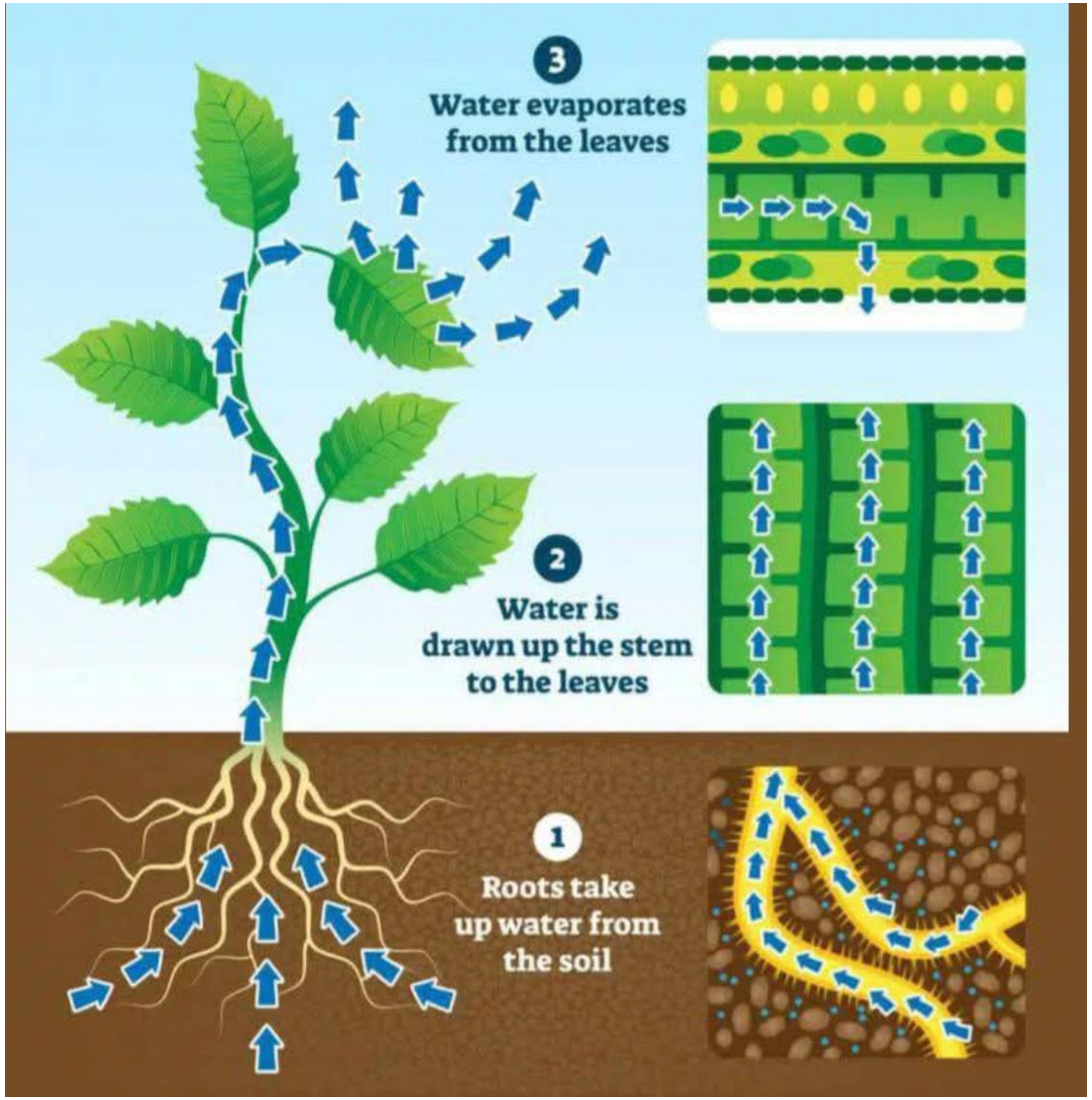


Evidence for the existence of root pressure

Water uptake from soil by roots

Driving Forces of Water Absorption by Roots

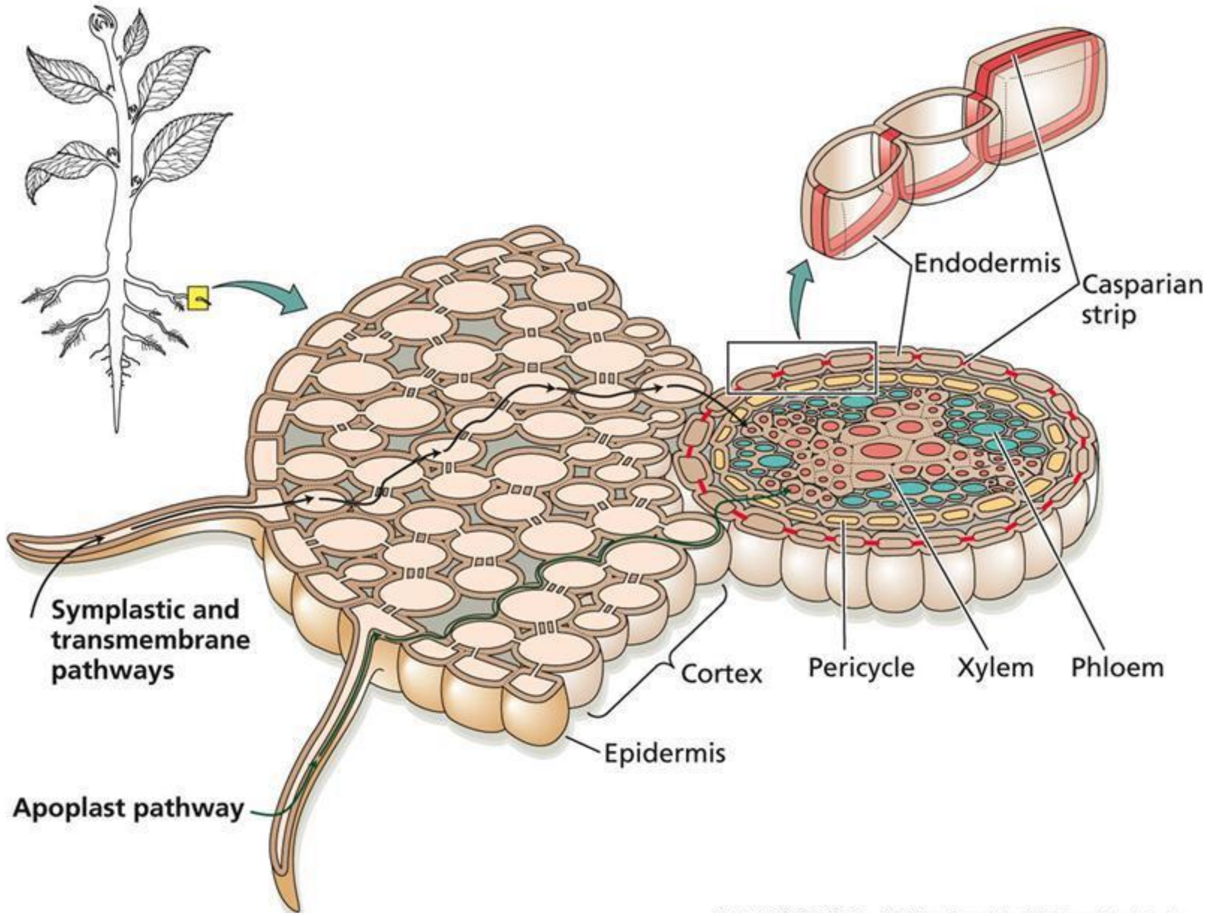
Passive absorption, water uptake driven by **transpirational pull**, with the driving force arising from transpiration.



Water transport pathway:

Atmosphere ← leaf stomata and mesophyll cell surfaces ← mesophyll cells ← leaf veins ← stem xylem ← root xylem ← roots

Water uptake from soil by roots

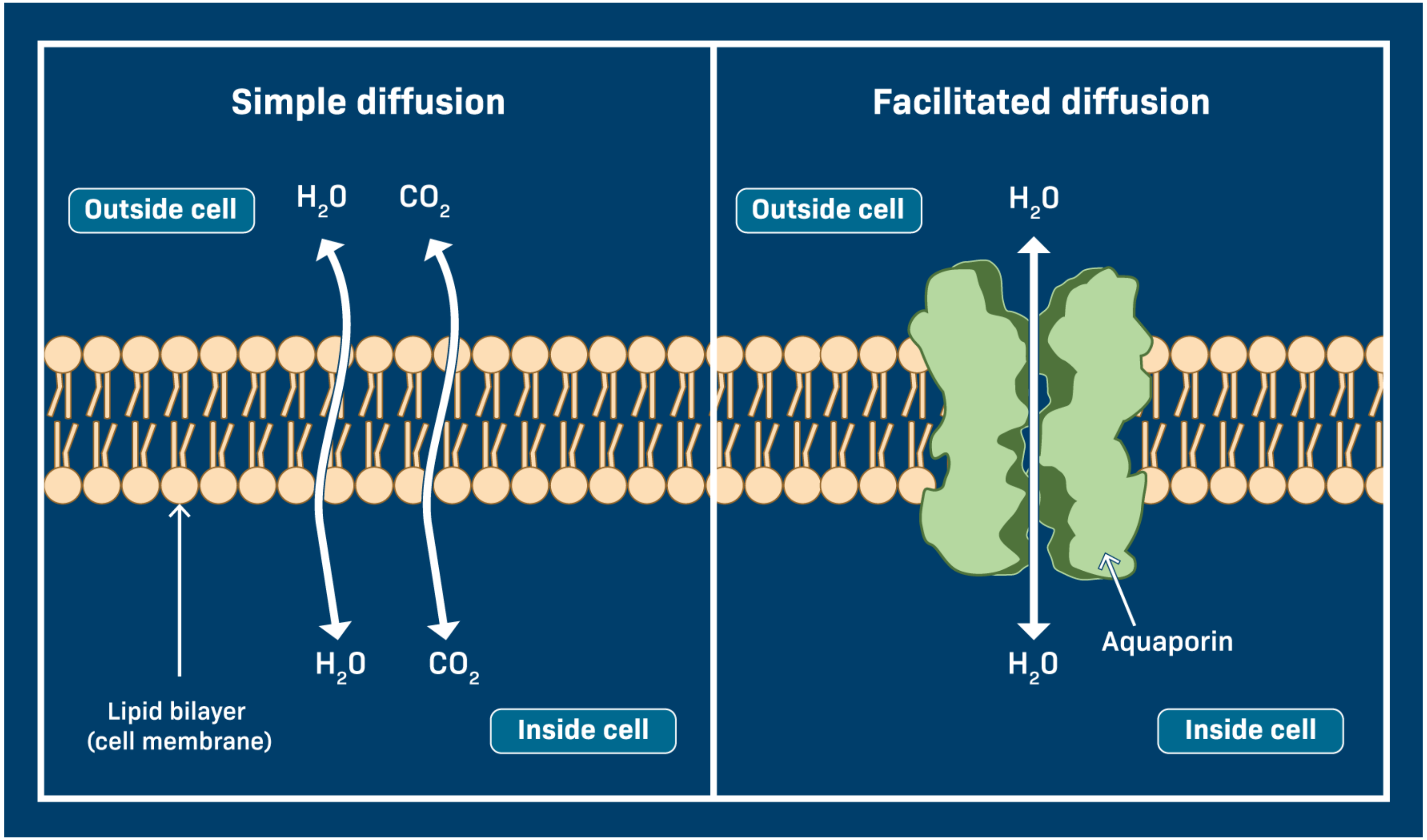


Water moves from root surface into xylem in root by three pathways:

- **Apoplast** pathway
- **Symplast** pathway
- **Transmembrane** pathway

Symplast path

Plant cells form an osmotic system due to the presence of the plasma membrane, which allows only small molecules to pass freely.



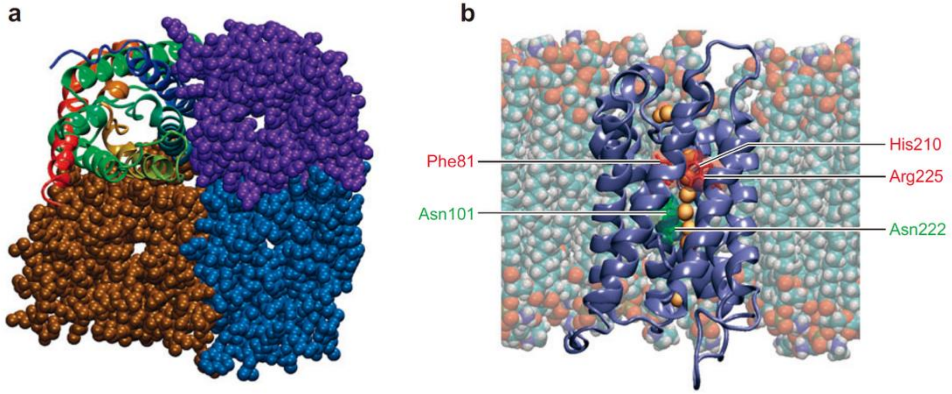
Symplast path

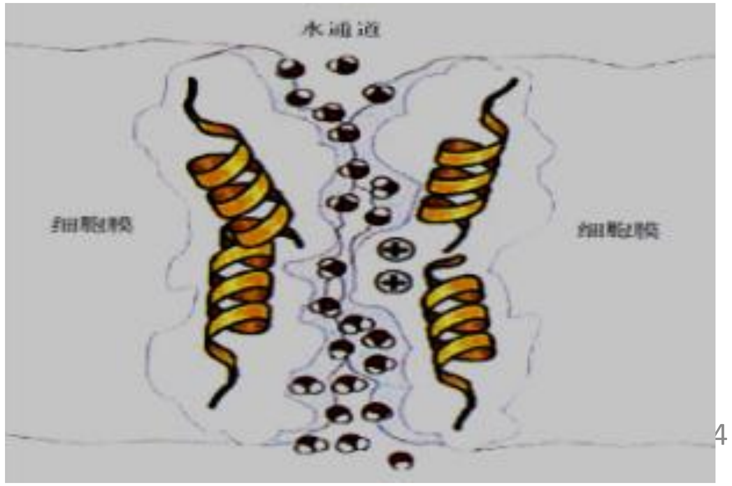
- **Simple diffusion: Water moves across the membrane from a region of higher water concentration to lower water concentration through random molecular motion.**
- **Bulk flow: Water moves across the membrane together with dissolved substances under the driving force of a pressure gradient.**

Symplast path

Aquaporins are specialized membrane proteins that facilitate rapid water movement across biological membranes by forming selective water channels.

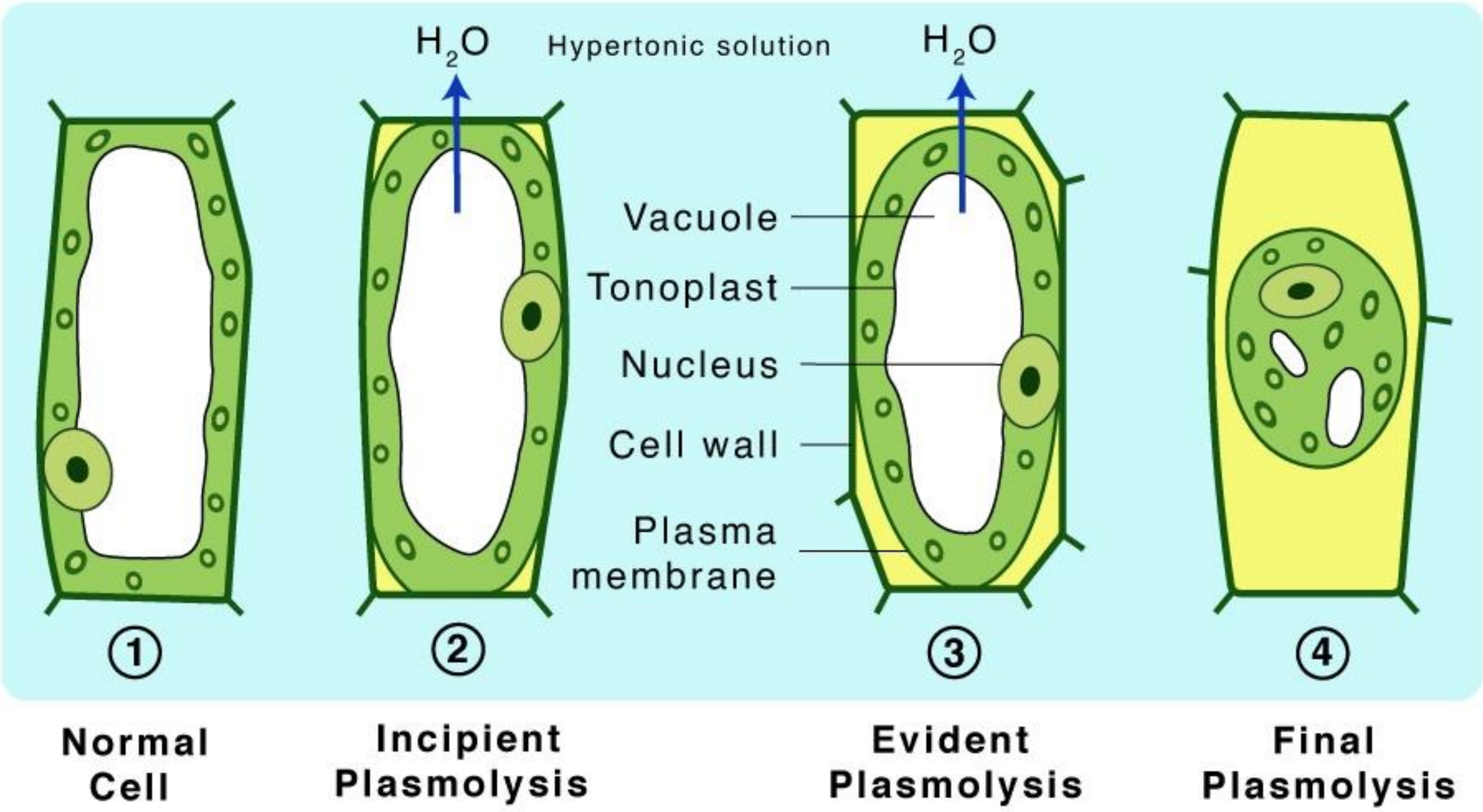
Several types of aquaporins have been identified, including **plasma membrane intrinsic proteins (PIPs)**, **tonoplast intrinsic proteins (TIPs)**, **Nod26-like intrinsic proteins (NIPs)**, **small basic intrinsic proteins (SIPs)**, and **X intrinsic proteins (XIPs)**.



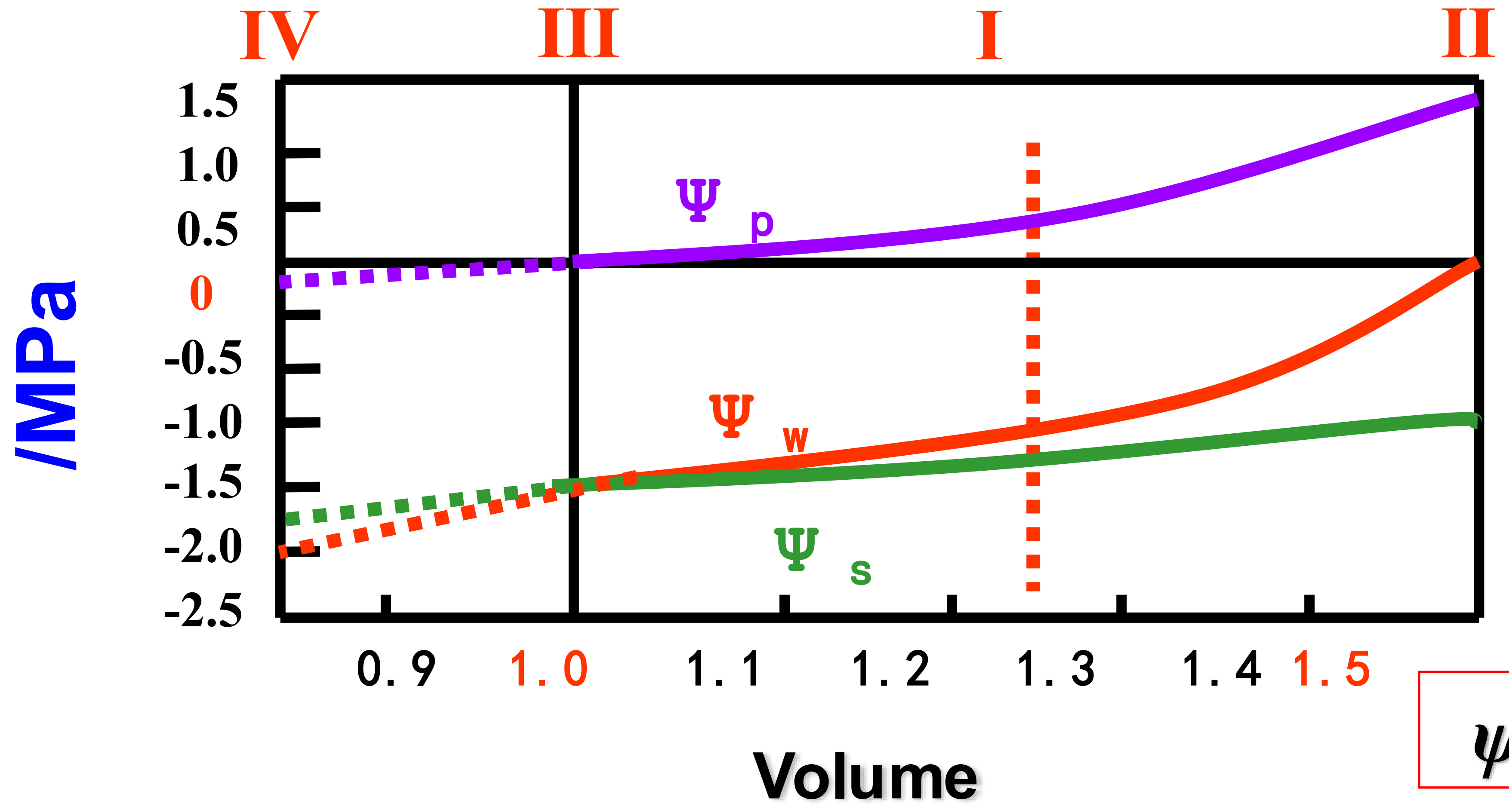


Plasmolysis (质壁分离) vs deplasmolysis (质壁分离复原)

The process of contraction or shrinkage of the cytoplasm and the plasma membrane of a plant cell due to excessive water loss is called plasmolysis, and the reverse process is known as deplasmolysis.

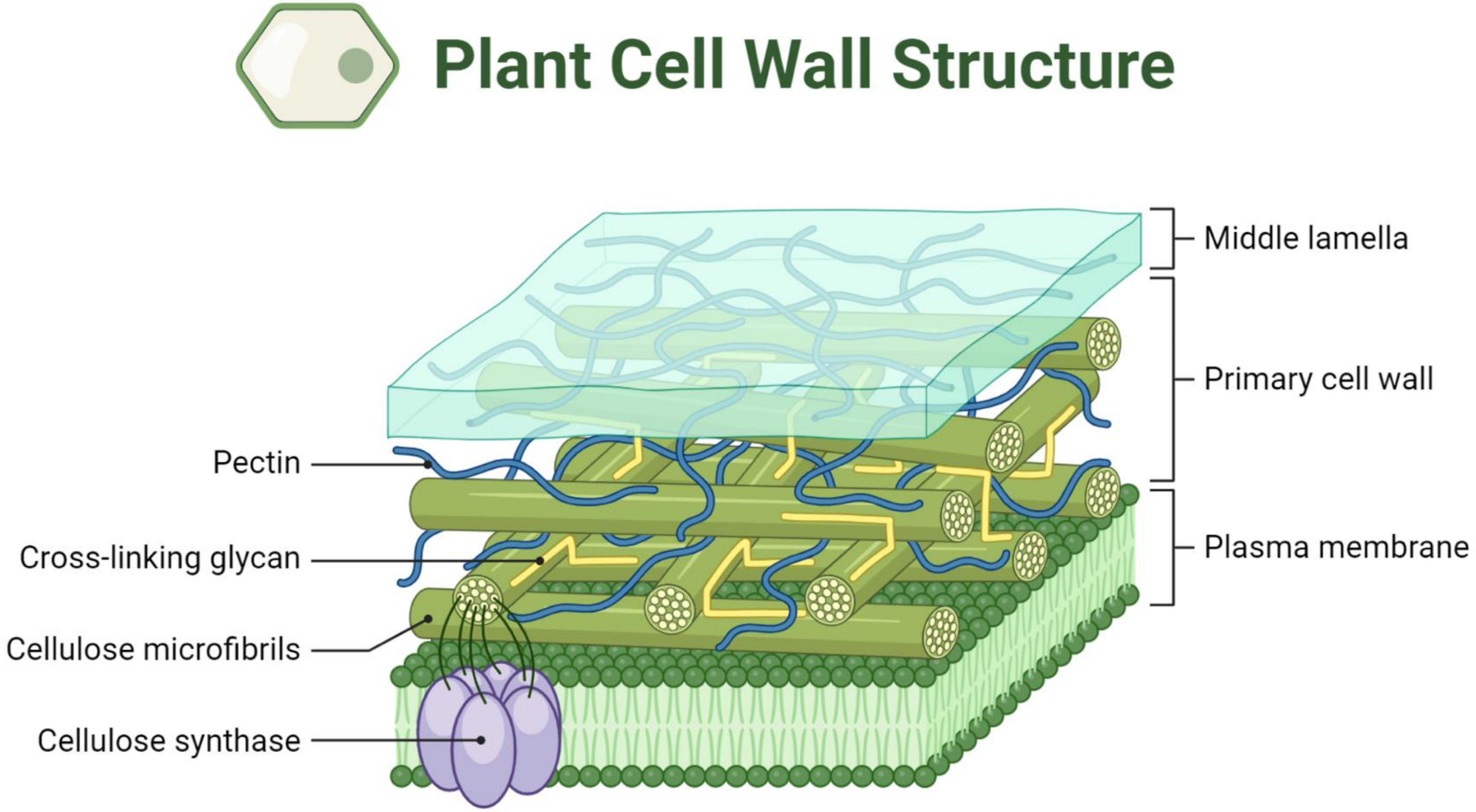


Cell water potential dynamics during Plasmolysis



$$\psi_w = \psi_s + \psi_p$$

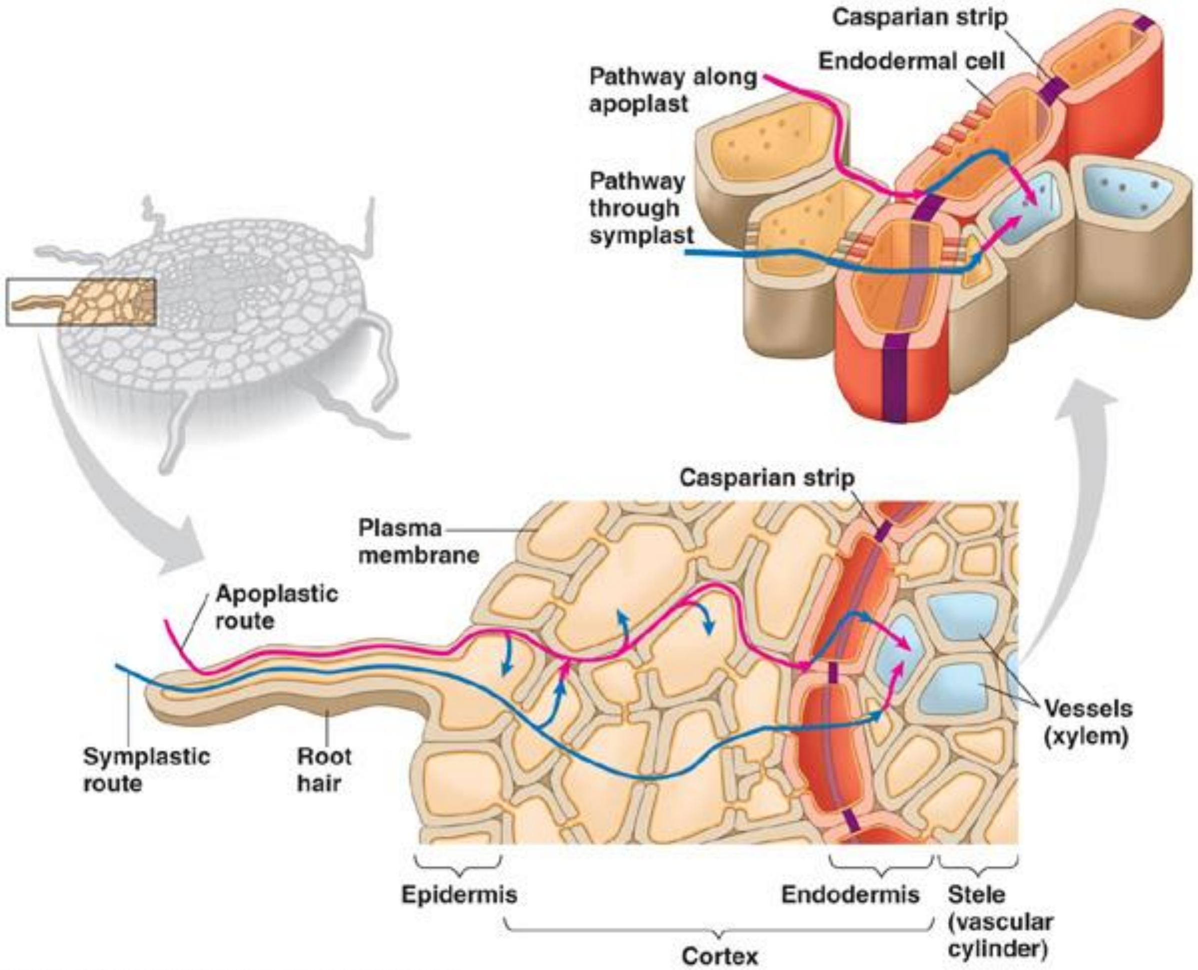
Apoplast Water

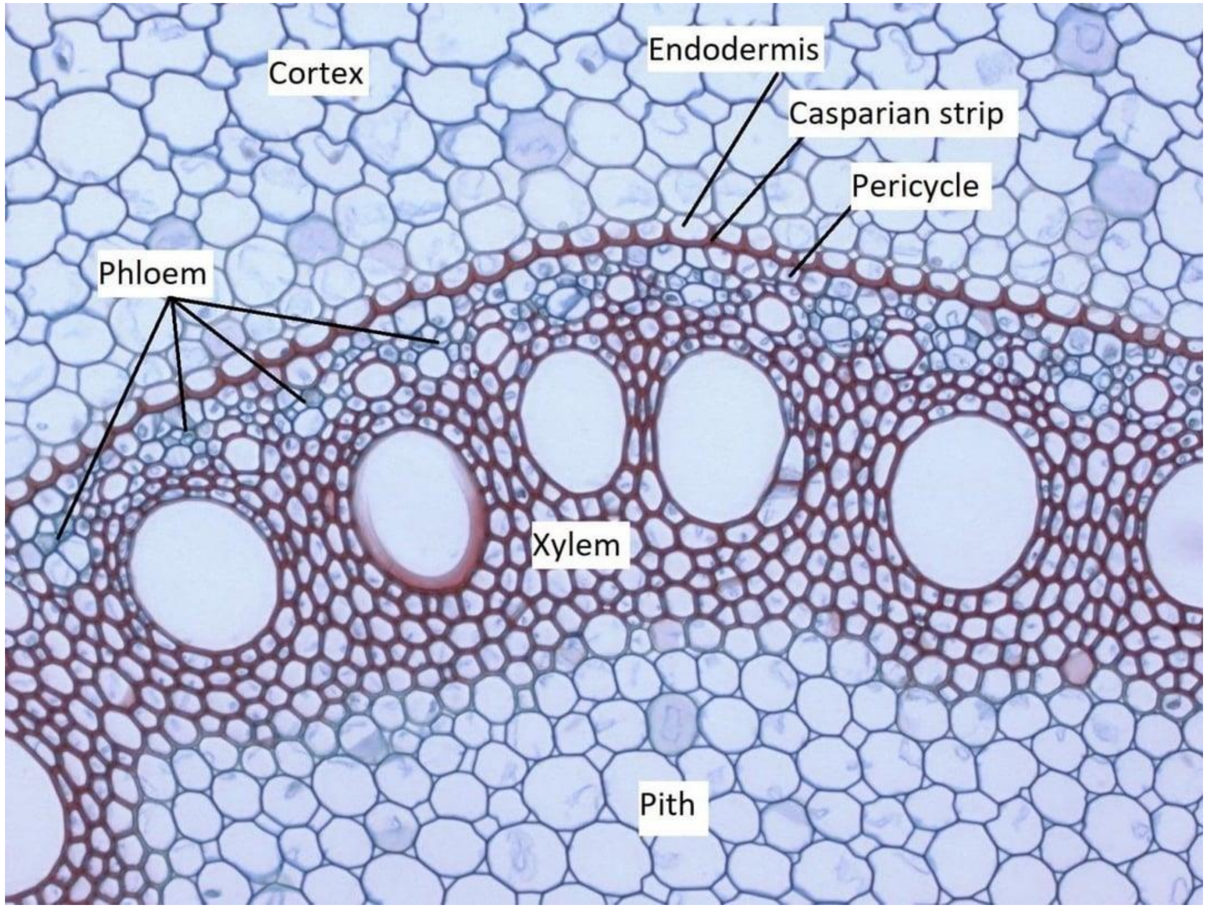


The plant cell wall contains abundant loosely arranged hydrophilic substances that can adsorb large amounts of water, forming a continuous water flow within the cell wall.

Apoplast Water

Due to the presence of the Casparian strip (凯氏带), apoplastic water must enter the cells before it can reach the xylem.





Factors Affecting Root Water Absorption

Root System

1. Greater root density generally enhances water absorption capacity.
2. Root permeability to water.
3. Distribution of roots within soil layers.
4. Root respiration rate and overall physiological activity.

Root density: Root length per unit volume of soil (cm/cm^3).

Soil Conditions

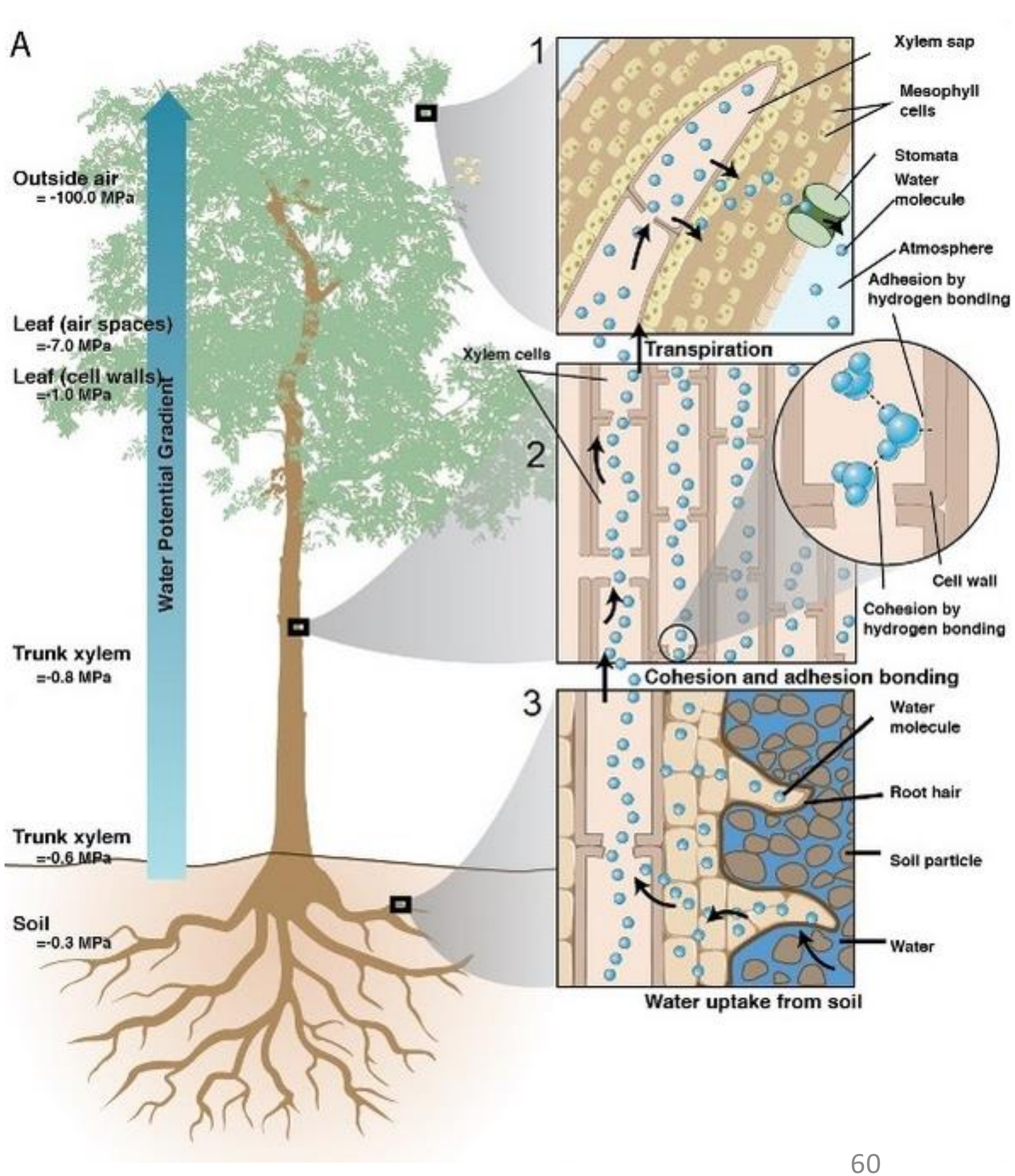
1. Soil available water content
2. Soil aeration status
3. Soil temperature
4. Soil solution concentration.

Fertilizer burn: In agricultural production, excessive or highly concentrated fertilizer application may increase the concentration of the soil solution around the roots to a level that prevents water uptake by plants.

Why do crops exhibit water-deficiency symptoms under excessive soil moisture?

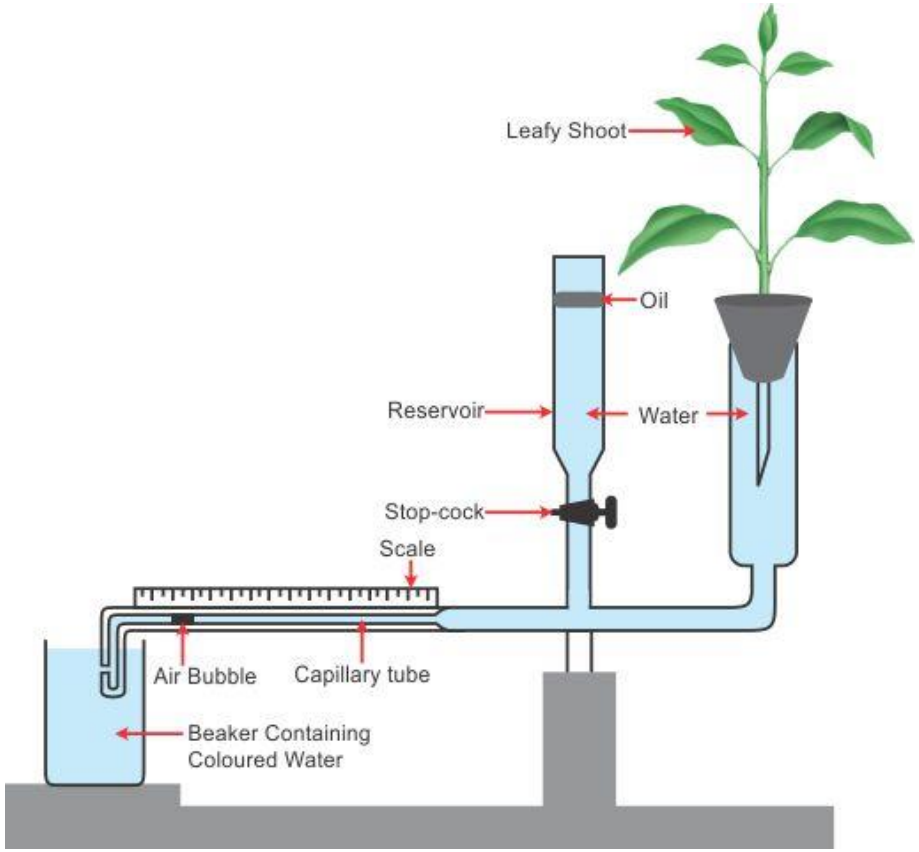
Outline

- Water status of plants
- Availability of water
- Water uptake from soil by roots
- **Water escapes from plants**
- **Water transport through plants**
- **Water Use & Stress**



Water escapes from plants

Transpiration is the process by which water within a plant is lost in the form of vapor from the plant surface (primarily the leaves), diffusing from the interior to the external environment.



Significance of Transpiration

1. **Transpirational pull is the primary driving force for water uptake in plants.**
2. **Transpiration reduces the temperature of the plant body and leaves.**
3. **The upward flow of xylem sap induced by transpiration facilitates the transport of inorganic ions absorbed by roots and organic substances synthesized in roots.**
4. **A negative effect of transpiration is excessive water loss, which lowers water-use efficiency.**

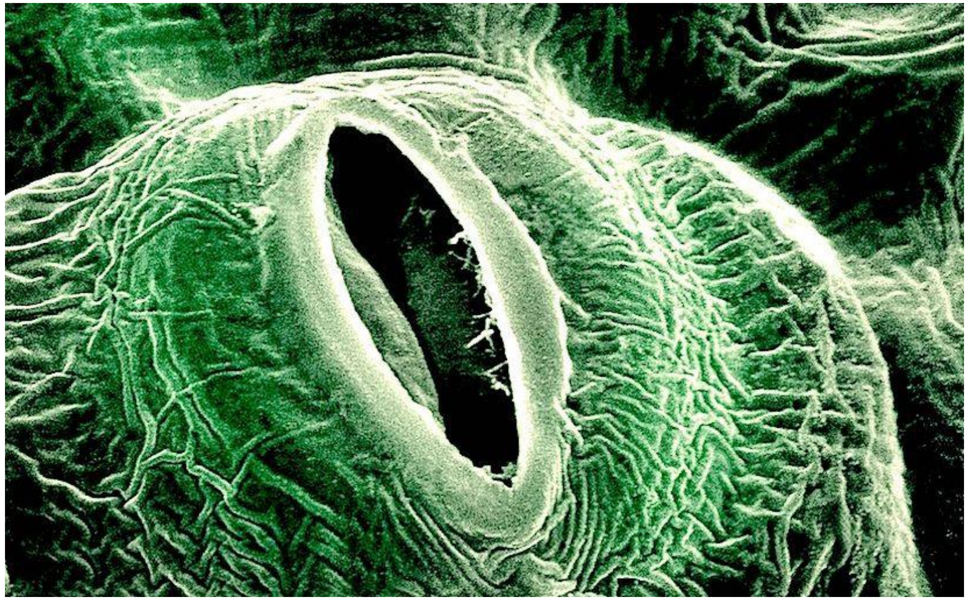
Measurement of Transpiration

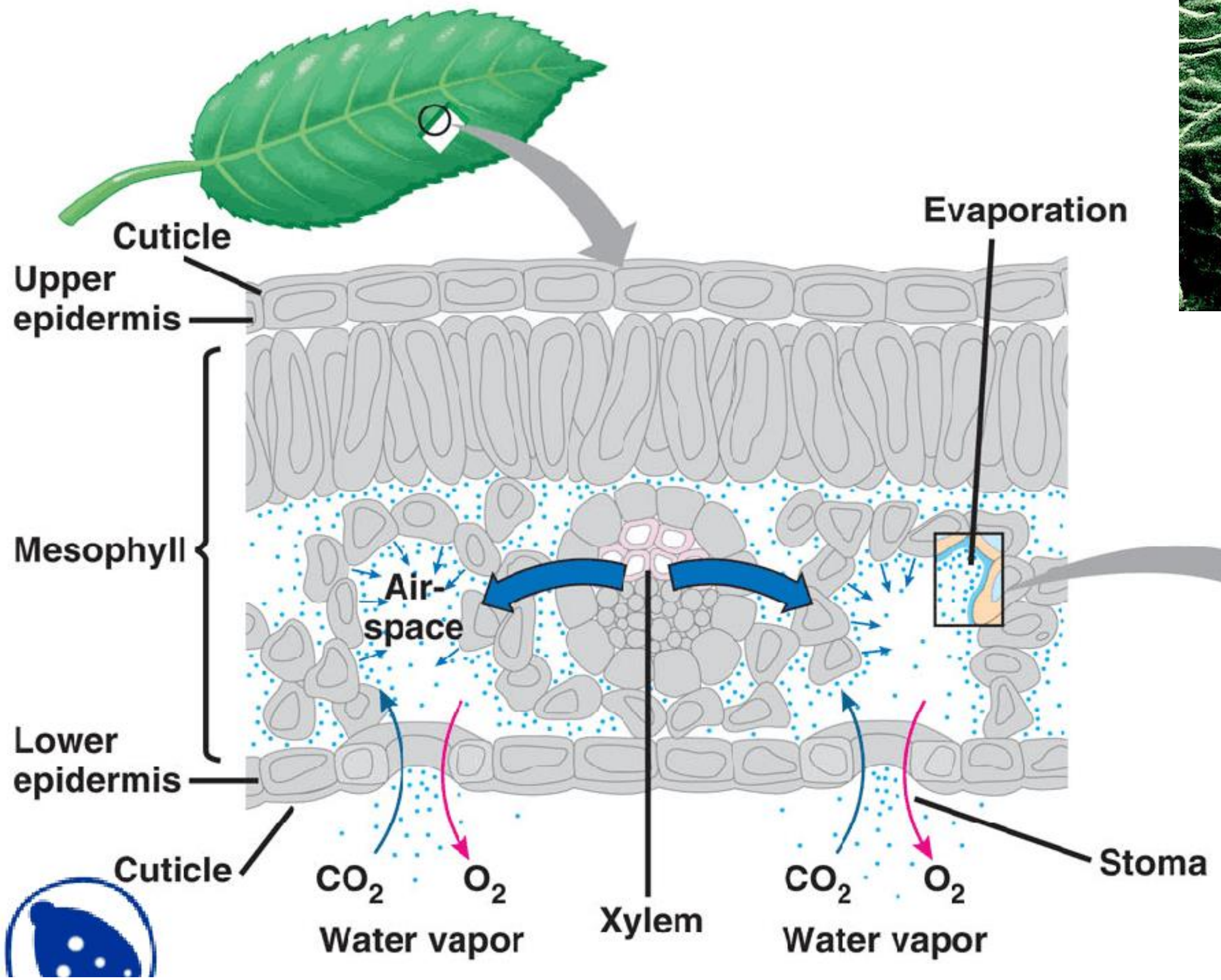
- **Transpiration rate** (蒸腾速率): The amount of water transpired per unit leaf area per unit time; usually expressed as g $H_2O \cdot m^{-2} \cdot h^{-1}$.
- **Transpiration ratio** (蒸腾效率): The amount of dry matter produced per kilogram of water consumed (i.e., dry matter/kg H_2O). In most plants, the transpiration ratio ranges from 1–8 g (dry matter)/kg.
- **Transpiration coefficient** (蒸腾系数): The amount of water (g) consumed to produce 1 g of dry matter (also termed water requirement). In most plants, the transpiration coefficient ranges from 125 to 1000.

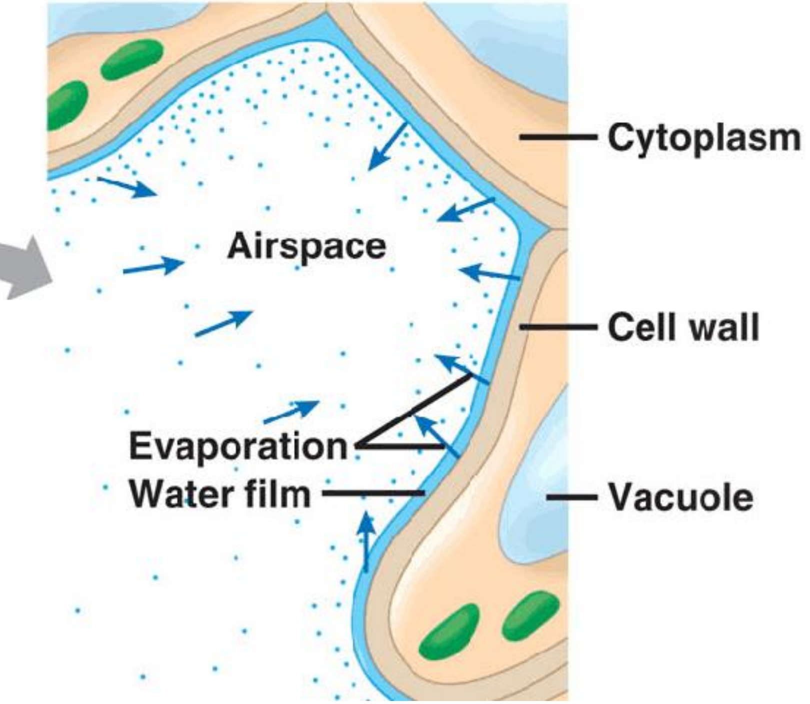
Measurement of Transpiration

Types of Transpiration

Stomatal transpiration

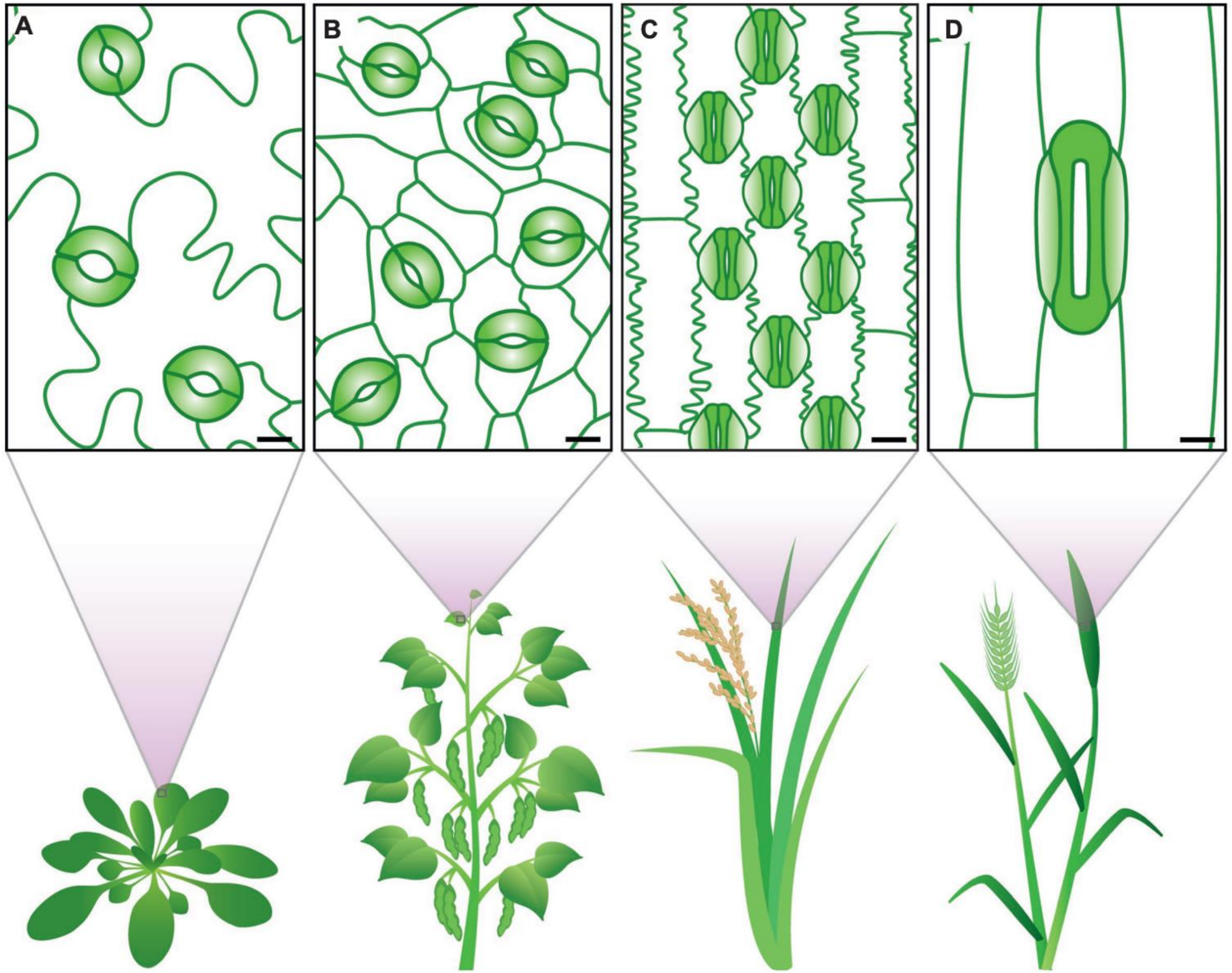


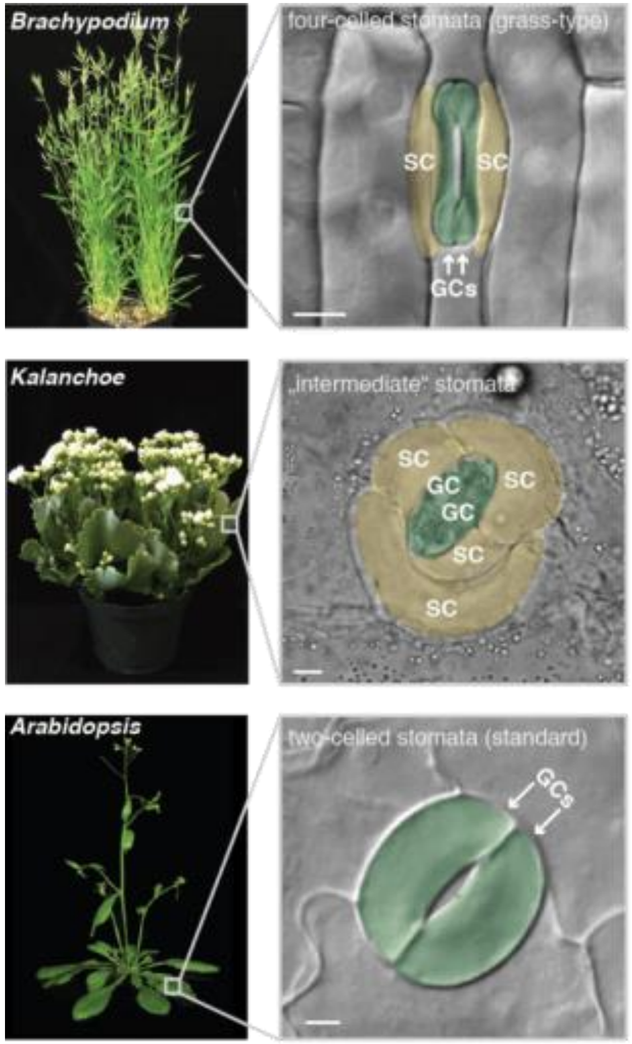




Stomatal transpiration

Stomatal traits vary between species

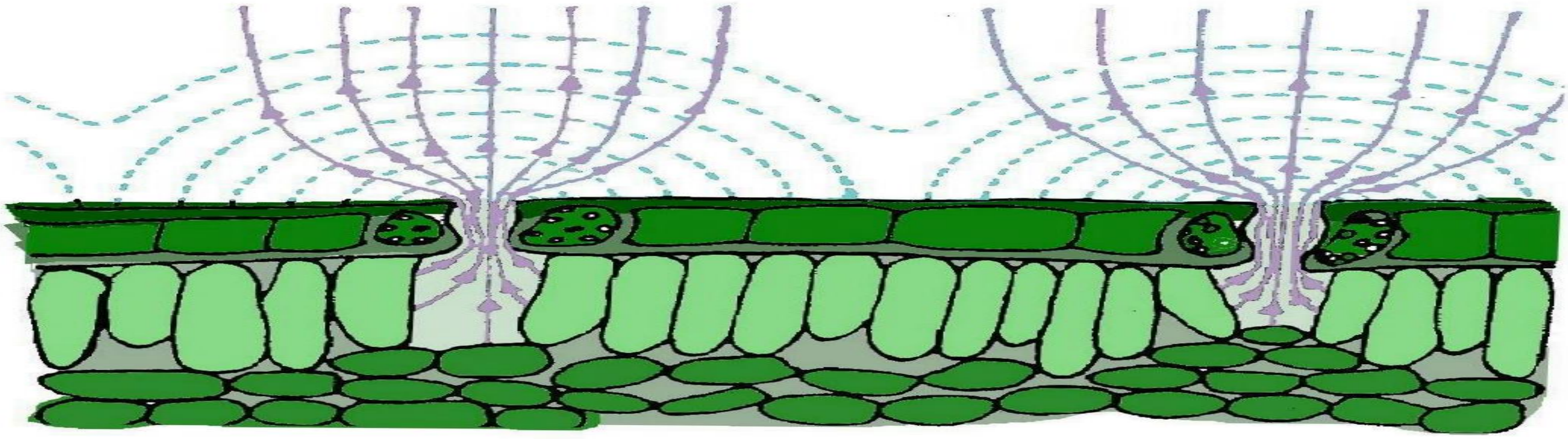




Stomatal transpiration

Small Pore Diffusion Law

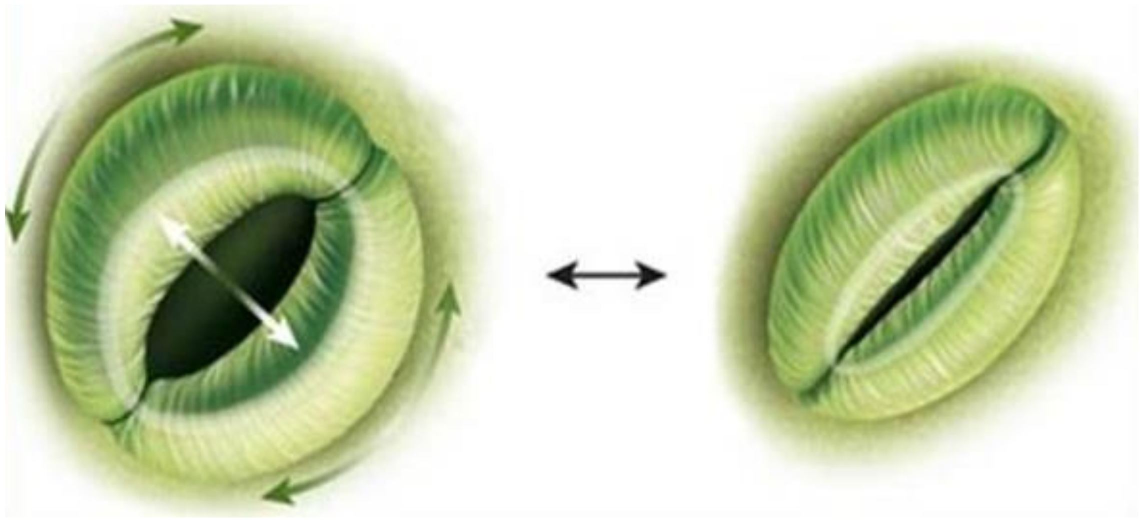
The rate of gas diffusion through a porous surface is not proportional to the total area of the small pores, but rather to the **perimeter** of the pores. This principle is referred to as the *small pore diffusion law*.



Stomatal transpiration

Stomatal Movement

Stomatal movement is the opening and closing of stomata by surrounding guard cells, regulating gas exchange(loss water and absorb CO_2).



Guard cell characteristics (vs. epidermal cells):

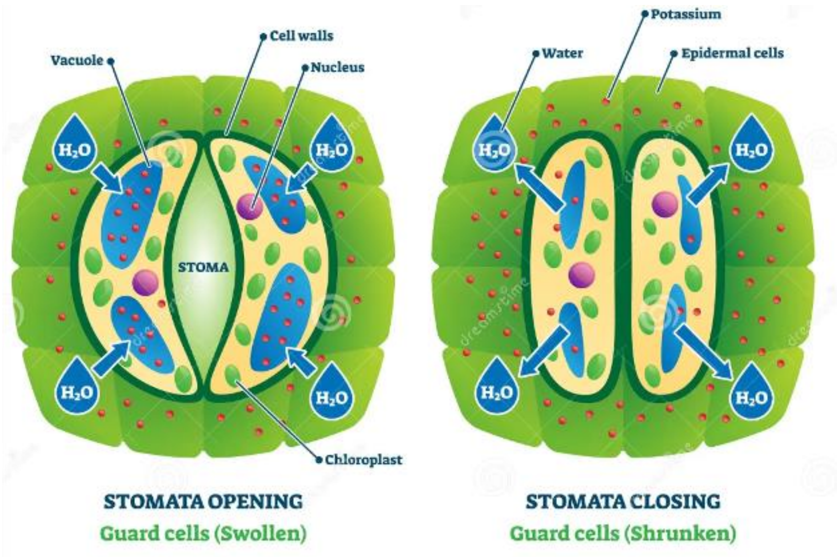
- Smaller cells with specialized structure; thin outer wall and thick inner wall, enabling rapid turgor changes.
- Radially arranged cellulose microfibrils reinforce the inner wall.
- Dense cytoplasm with abundant organelles.

Stomatal transpiration

Stomatal Movement — **The Driving Force: Turgor Pressure**

Stomatal movement is a hydraulic process. The "open" or "closed" state depends entirely on the **Turgor Pressure** within the guard cells.

High Turgor (Turgid): Water enters the guard cells --- cells swell --- **Stoma Opens**.



Low Turgor (Flaccid): Water leaves the guard cells --- cells shrink --- **Stoma Closes**.

Stomatal transpiration

Stomatal Movement

The Classical Starch-Sugar Hypothesis

Proposed by Lloyd (1908) and later refined by Sayre (1923), this was the first major attempt to explain stomatal mechanics based on enzymatic activity.

- **Mechanism:** It suggests that in the light, photosynthesis reduces CO_2 concentration in the leaf, increasing the pH of guard cells. This alkalinity activates the enzyme phosphorylase, which converts insoluble starch into soluble sugars (glucose).
- **Osmotic Shift:** The increase in soluble sugar lowers the osmotic potential, drawing water into the guard cells via osmosis.
- **Shortcoming:** This model is largely considered outdated because the conversion of starch to sugar is too slow to account for the rapid stomatal movements observed in nature.

$$\text{Starch} \underset{\text{Night}}{\overset{\text{Phosphorylase (day)}}{\rightleftharpoons}} \text{Sugar}$$

Stomatal transpiration

Stomatal Movement **The Ion Flux (K^+ and H^+) Model**

Proposed by Fujino (1967) and expanded by Levitt (1974), this is currently the most widely accepted physiological model. It emphasizes the role of malate and potassium ions.

The movement of water is dictated by the movement of solutes (ions). This is the "Engine" that drives the osmotic gradient.

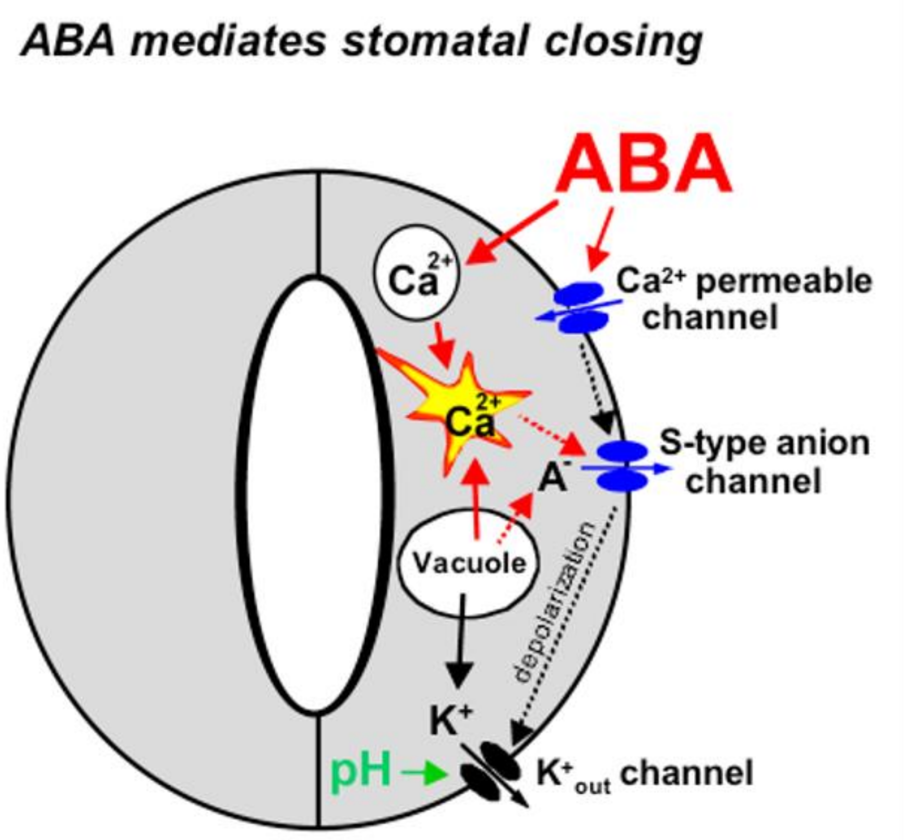
- **Proton Pump (H^+-ATPase):** This is the master switch triggered by **light**. It pumps H^+ out of the cell, creating a negative electrical charge inside.
- **Potassium (K^+) Influx:** To balance the negative charge, K^+ ions rush in through voltage-gated channels.
- Malate Synthesis: To maintain charge balance, organic acids (primarily malic acid) are synthesized. Starch is broken down into Phosphoenolpyruvate (PEP), which combines with CO_2 to form malate.

Stomatal transpiration

Stomatal Movement **ABA-Mediated Signaling Hypothesis (closure)**

While the K^+ models focus on opening, this hypothesis explains how plants respond to stress via Abscisic Acid (ABA).

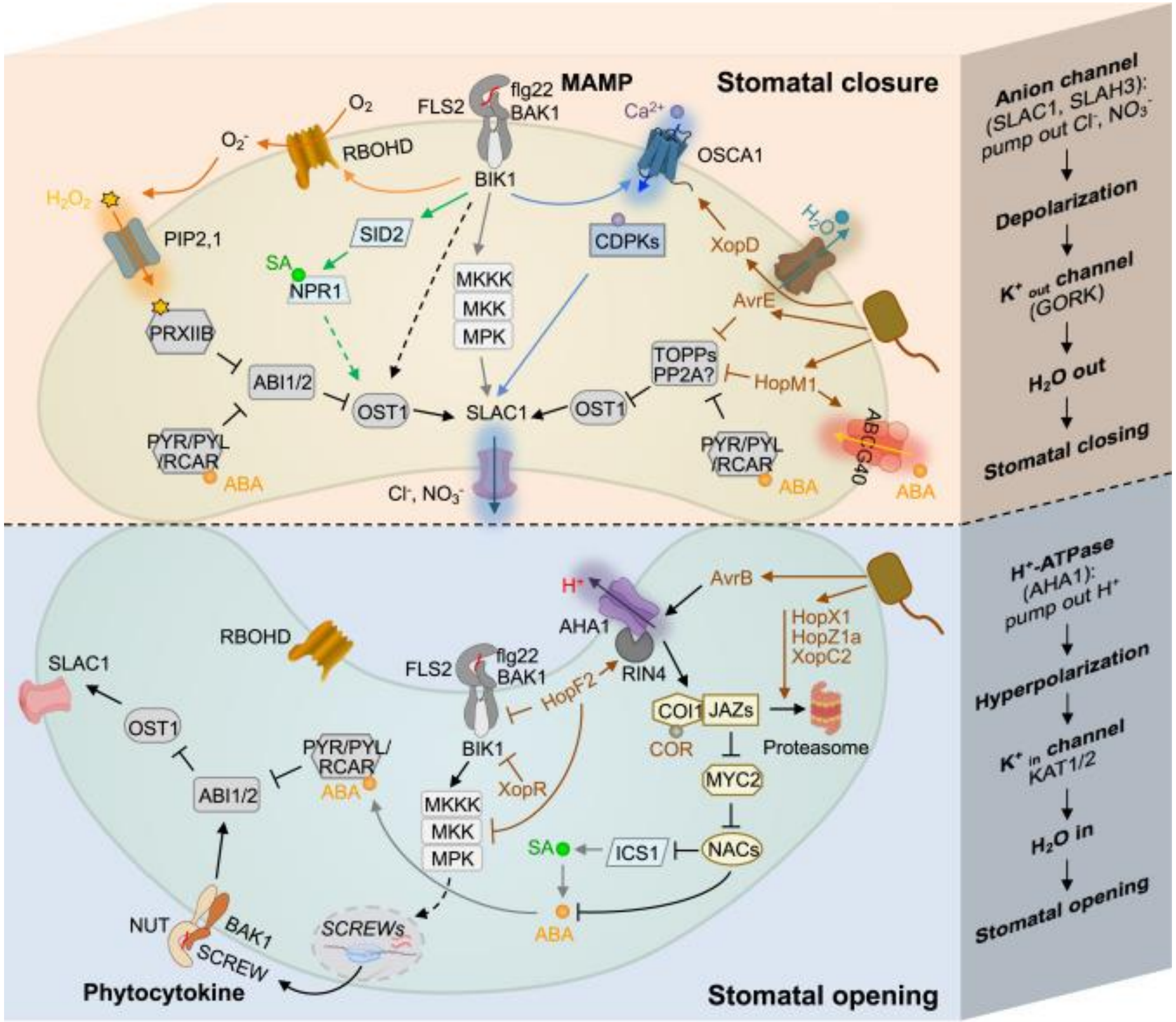
- **Calcium as a Second Messenger**: ABA binds to receptors on the guard cell, triggering an increase in cytosolic free Ca^{2+}.
- **Anion Channels**: Rising calcium levels activate S-type (Slow) and R-type (Rapid) anion channels, allowing Cl^- and malate to exit the cell.
- **Depolarization**: The loss of anions depolarizes the membrane, which triggers the efflux of K^+ ions.



Stomatal transpiration

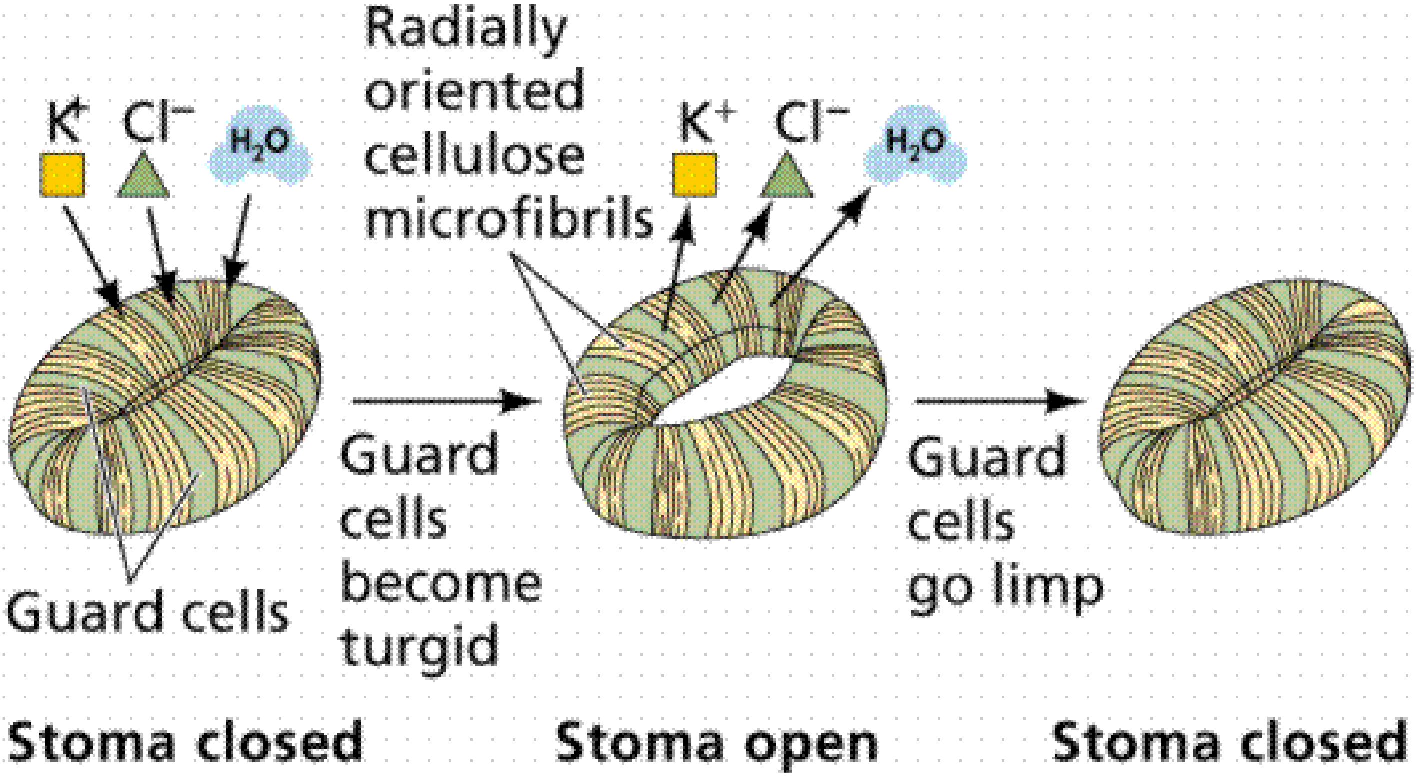
Stomatal Movement

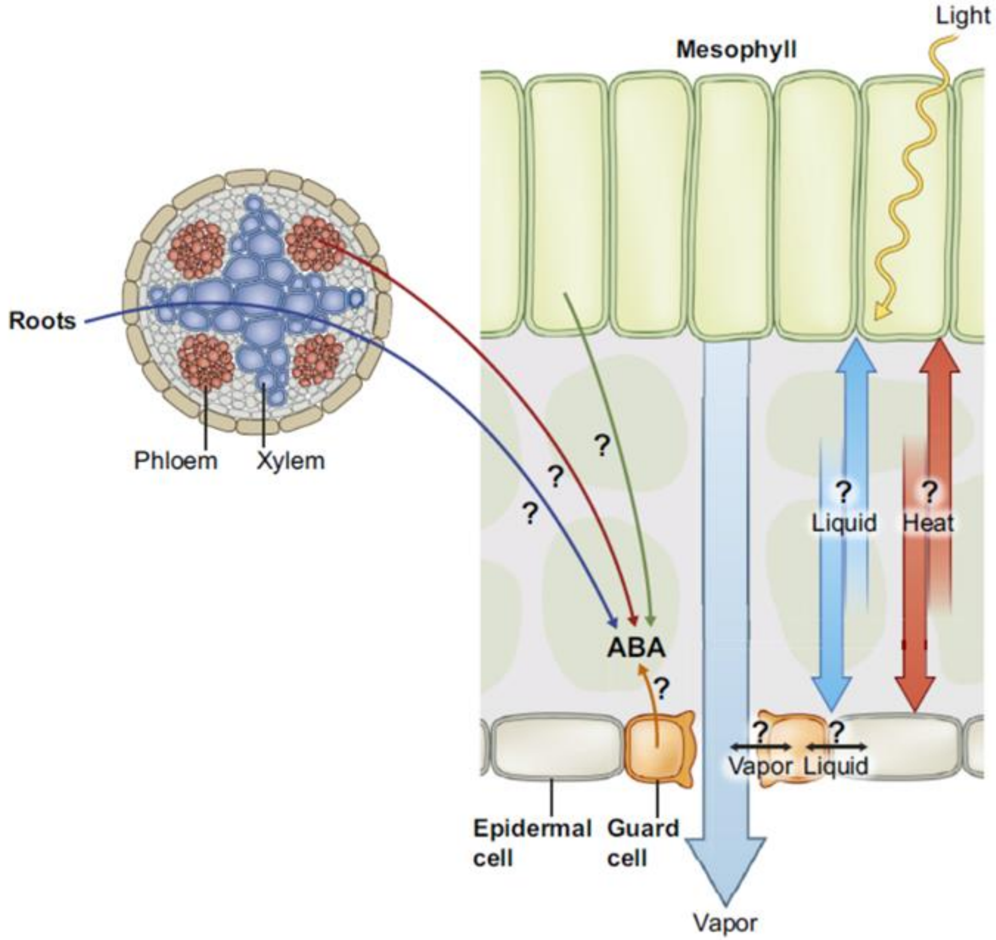
The Ion Flux (K^+ and H^+) and ABA coregulated Model



Stomatal transpiration

Stomatal Movement





Stomatal transpiration

Stomatal Movement in response to environmental changes

(1) CO_2 concentration

Low intercellular CO_2 partial pressure promotes stomatal opening, whereas high CO_2 induces closure.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HOME > SCIENCE ADVANCES > VOL. 8, NO. 49 > STOMATAL CO_2/BICARBONATE SENSOR CONSISTS OF TWO INTERACTING PROTEIN KINASES, RAF-LIKE HT1...

RESEARCH ARTICLE | PLANT SCIENCES

Stomatal CO_2/bicarbonate sensor consists of two interacting protein kinases, Raf-like HT1 and non-kinase-activity requiring MPK12/MPK4

YOHEI TAKAHASHI, KRYSTAL C. BOSMANS, PO-KAI HSU, KARNELIA PAUL, CHRISTIAN SEITZ, CHUNG-YUEH YEH, YUH-SHUH WANG, DMITRY YARMOLINSKY, MAIJA SIERLA, [...], AND JULIAN I. SCHROEDER +7 authors Authors Info & Affiliations

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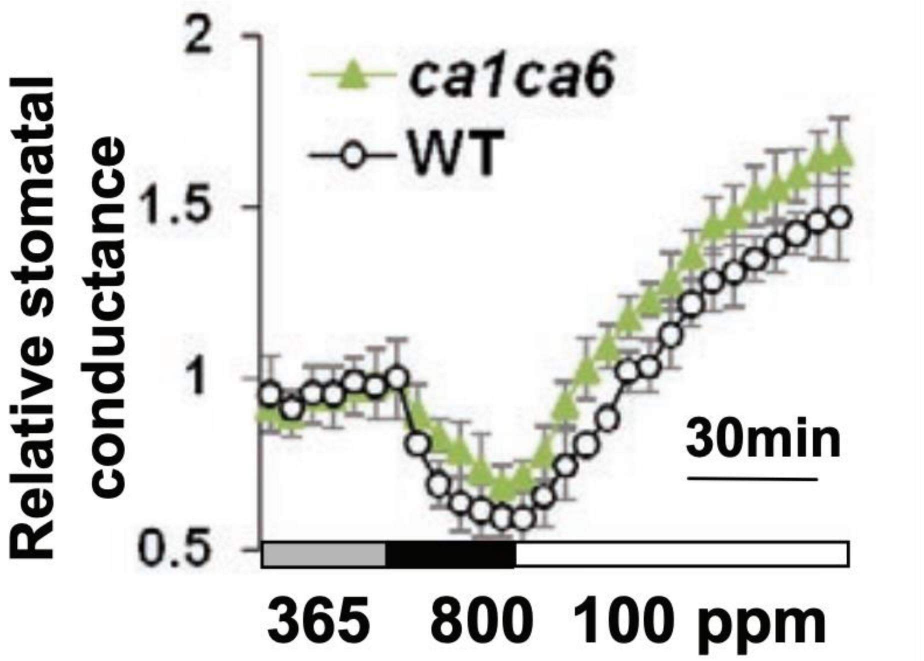


10.1038/ncb2009

The CO_2 sensing mechanism is not yet fully clarified.

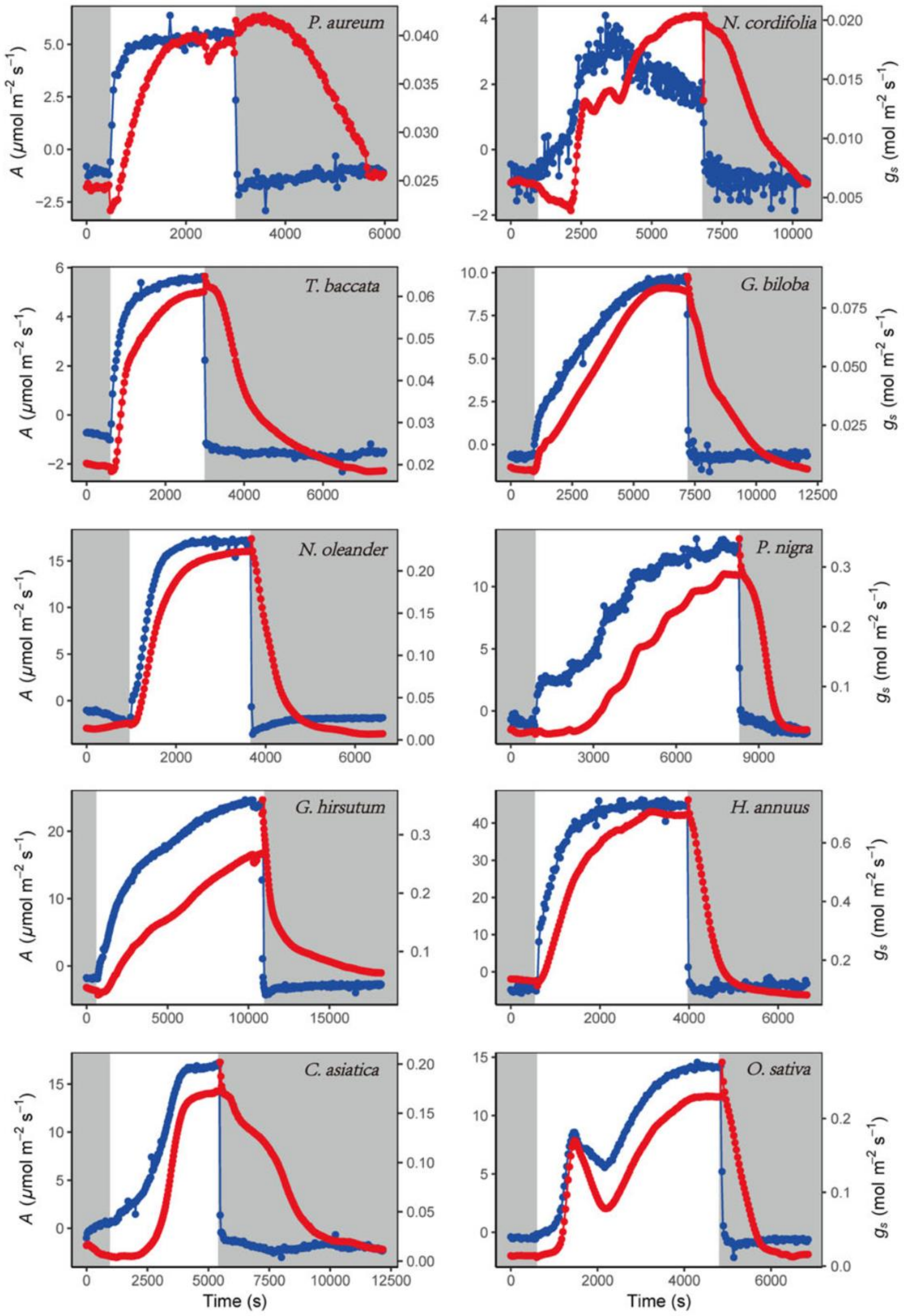
Stomatal transpiration

Stomatal Movement in response to environmental changes

(2) Light

Light generally induces stomatal opening, while darkness causes closure. Regulation depends on light quality.

- Blue light is perceived directly by guard cells (PHOT1 and PHOT2).
- Red light acts indirectly via photosynthetic activity in mesophyll cells.



Stomatal transpiration

Stomatal Movement in response to environmental changes

(3) Temperature

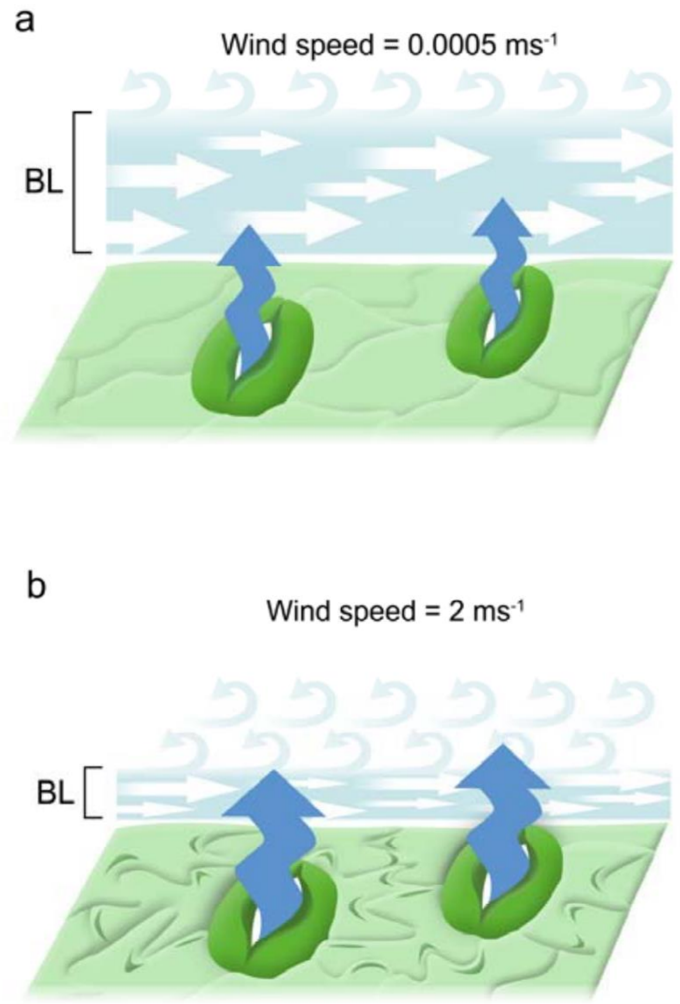
Stomatal aperture typically **increases with rising temperature**, reaching a maximum around 30 °C, and declines above 35 °C.

(4) Water status

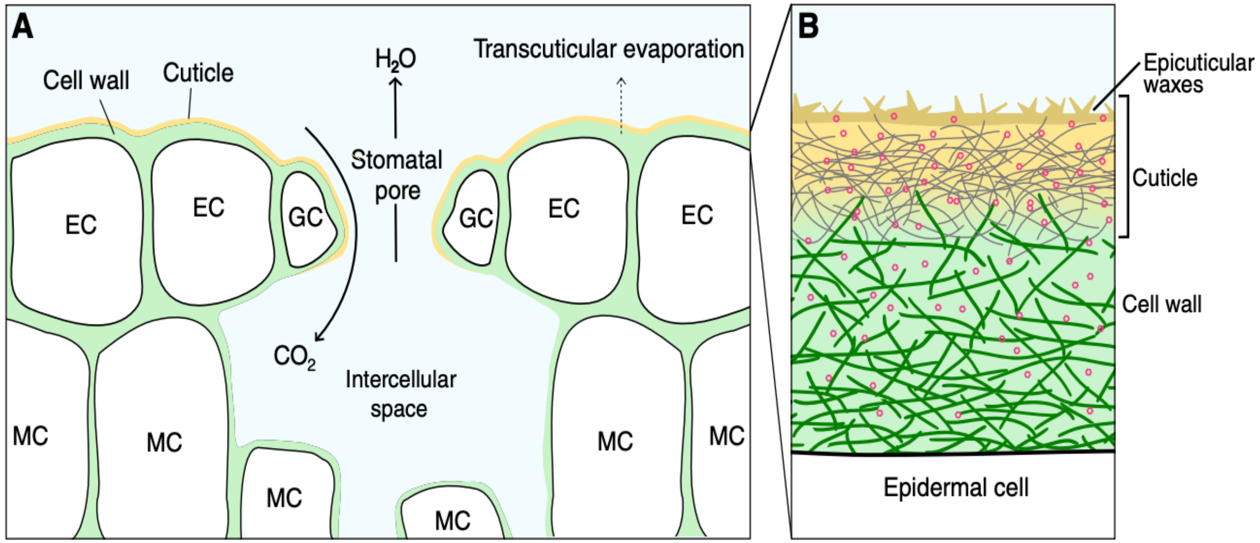
Decreased water potential directly reduces guard cell turgor, leading to stomatal closure.

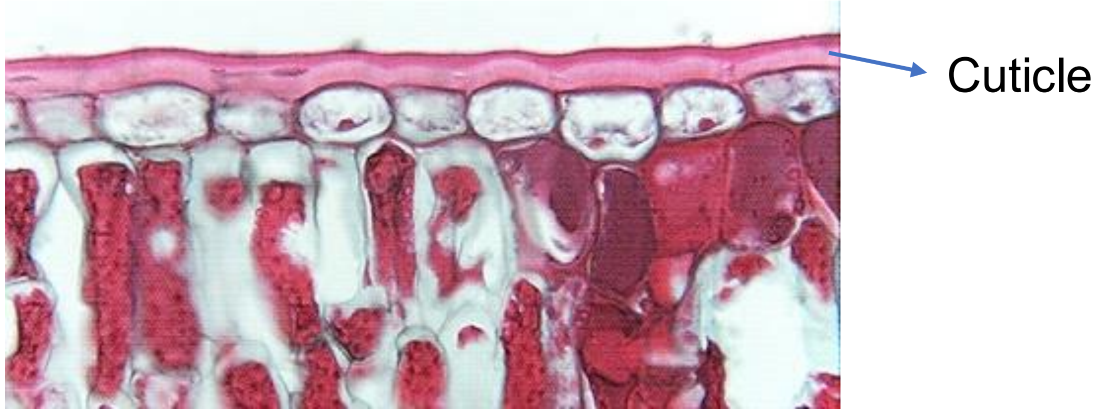
(5) Wind

Strong wind can induce stomatal closure.



Cuticular transpiration: water evaporates from the outer cuticle surface into the atmosphere.

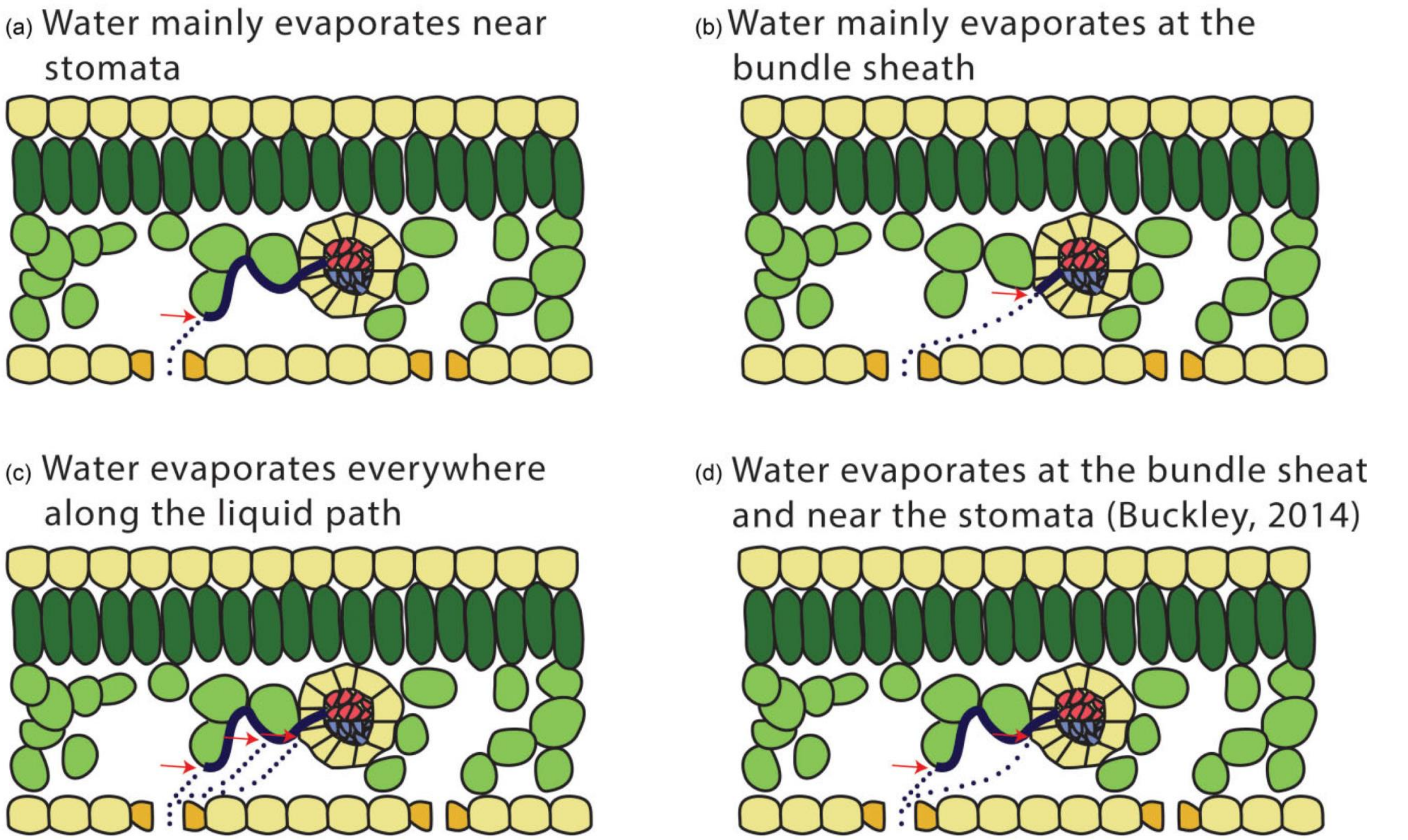




The loss of water from the plants through the lenticels is known as **lenticular transpiration**.

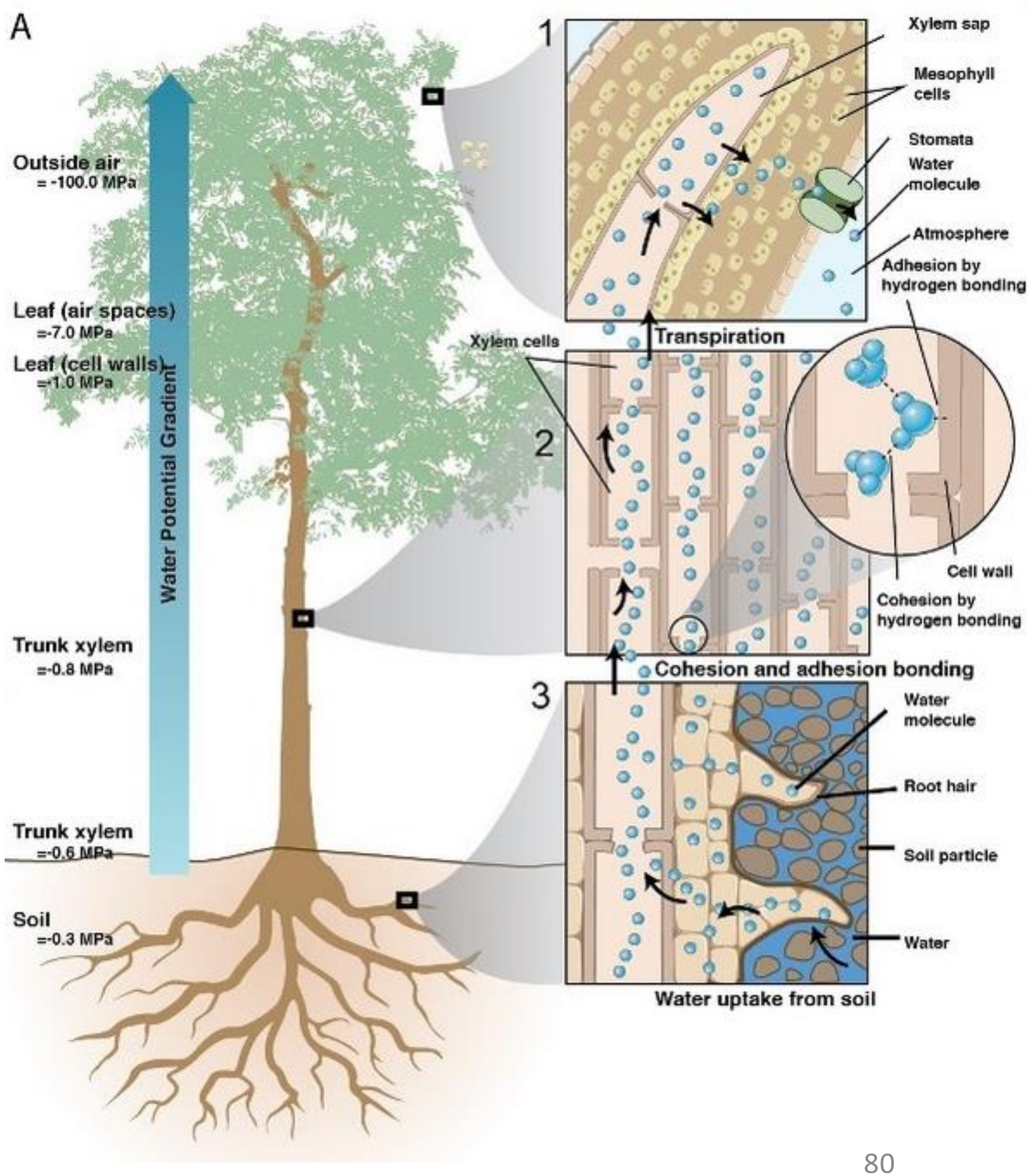
Water escapes from plants

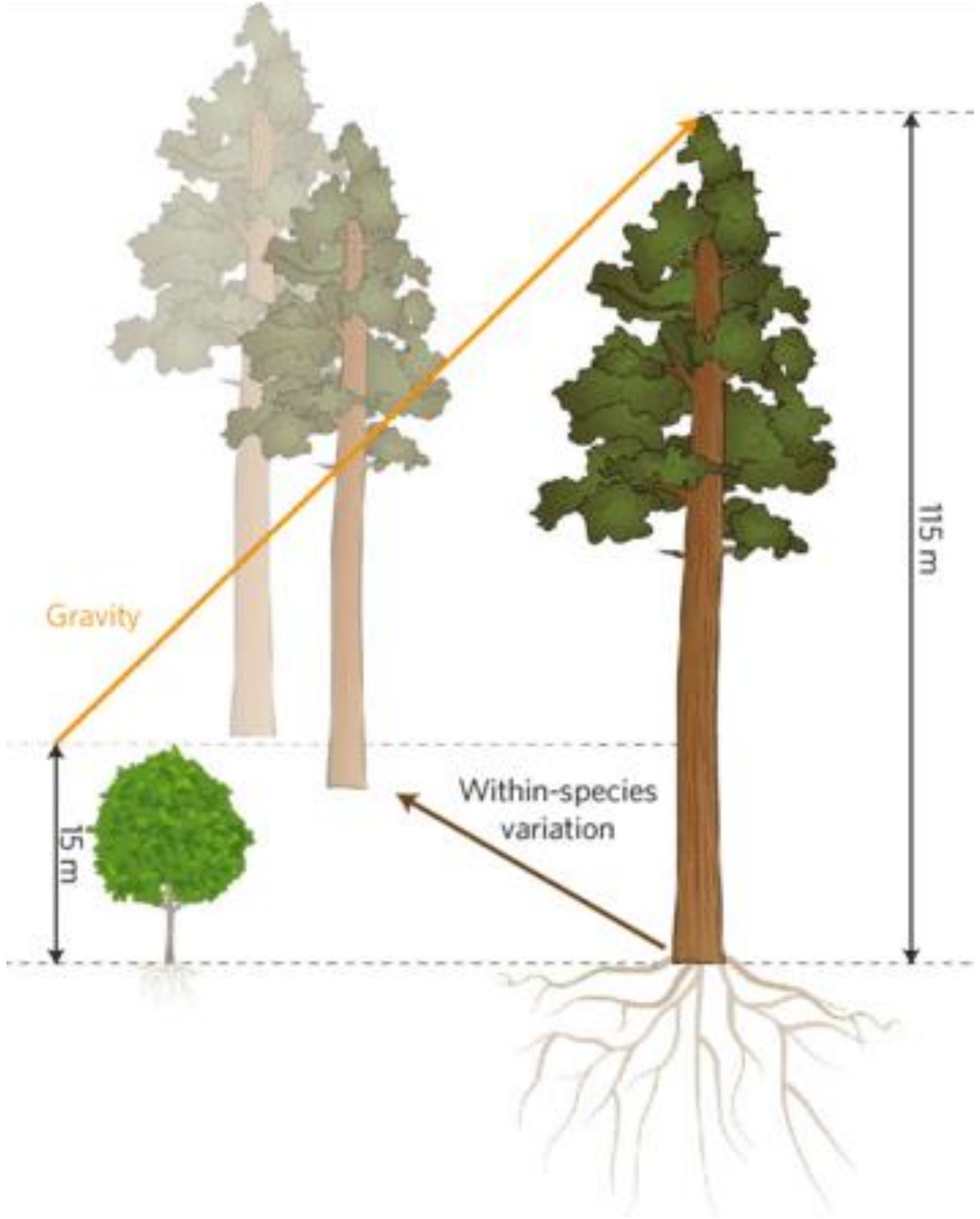
Question: Where does the water evaporate?



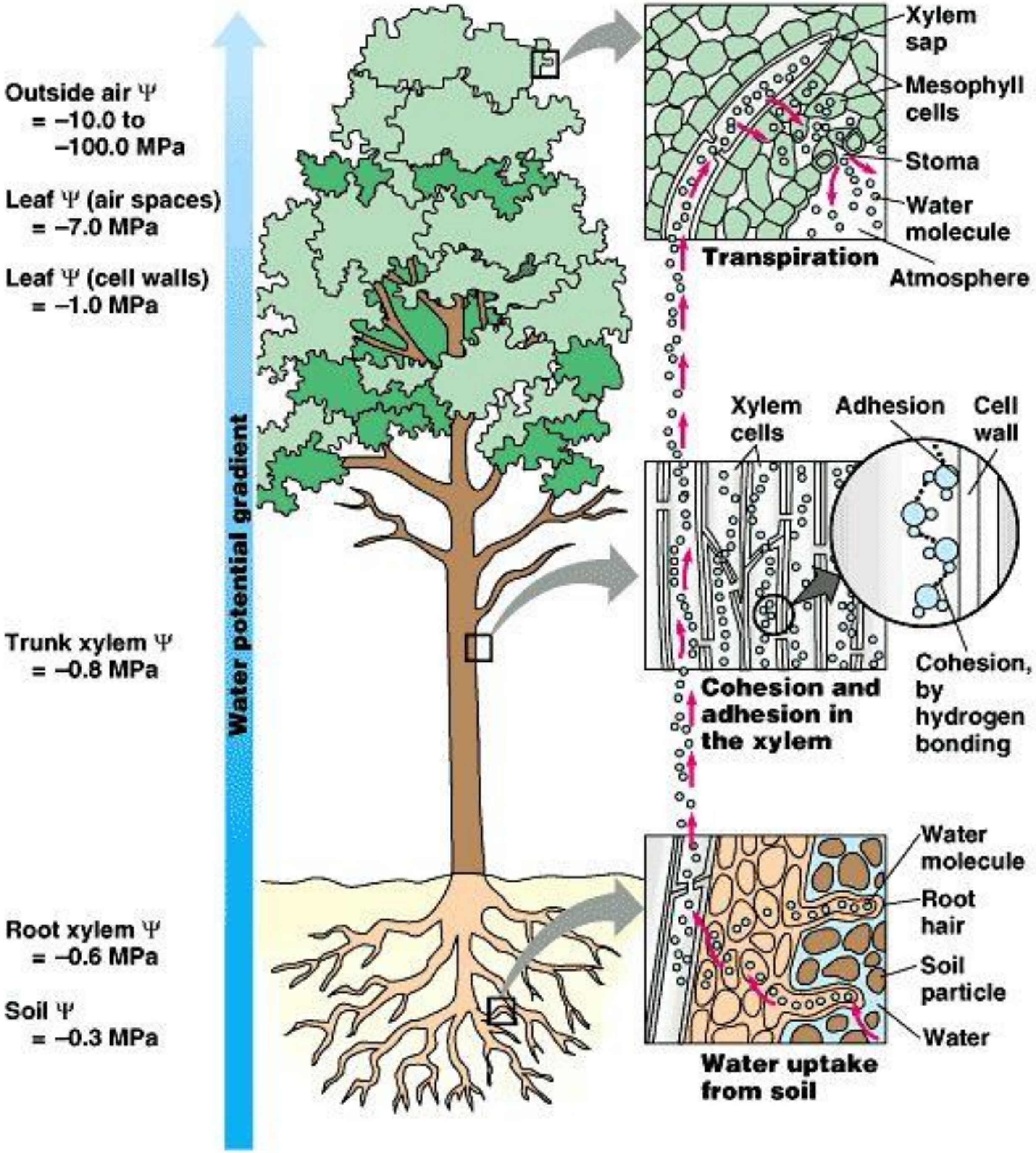
Outline

- Water status of plants
- Availability of water
- Water uptake from soil by roots
- Water escapes from plants
- **Water transport through plants**
- **Water Use & Stress**





How does water transport in plants?



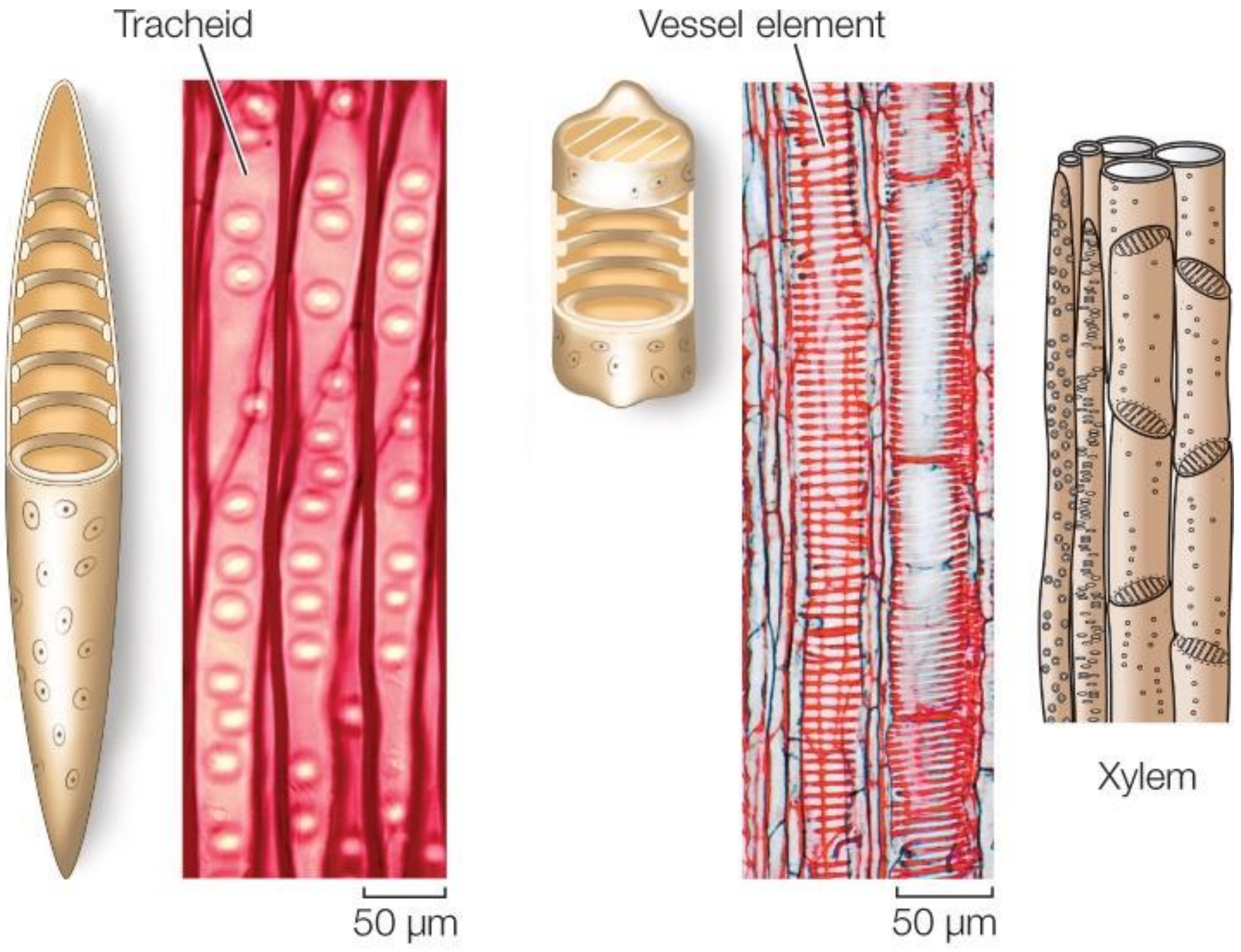
Pathway of Water Transport in Plants

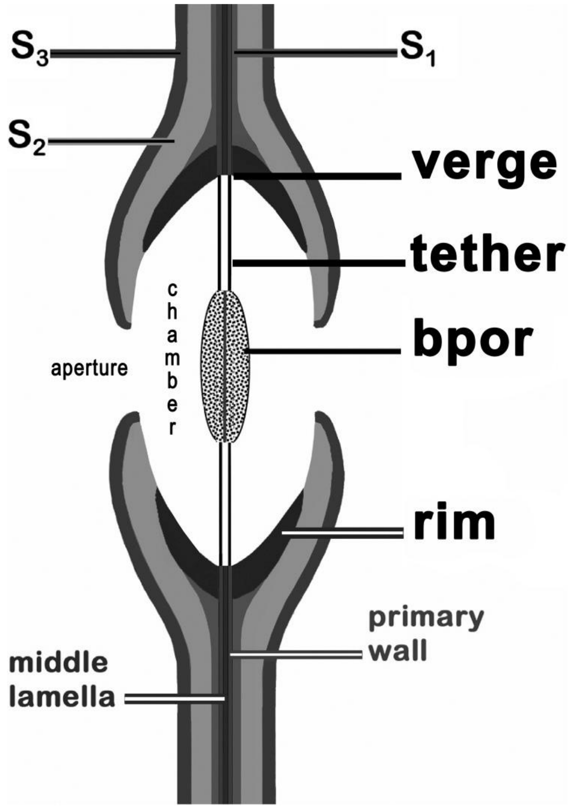
Soil water → root hair → cortex → stele → root xylem → stem xylem → petiole xylem → leaf vein xylem → mesophyll cells → intercellular spaces → substomatal cavity → stomata → atmosphere

Water movement continuous system from soil → plant → atmosphere, known as the **soil–plant–atmosphere continuum (SPAC)**.

Water Transportation

vessel elements and **tracheids**



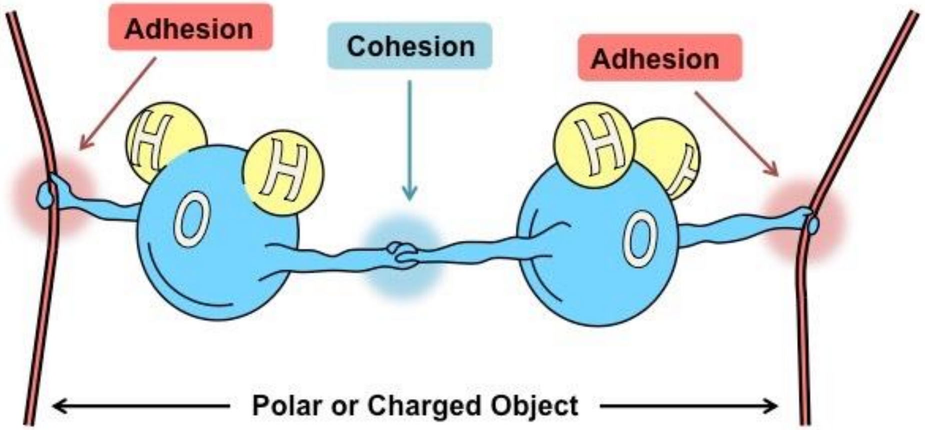


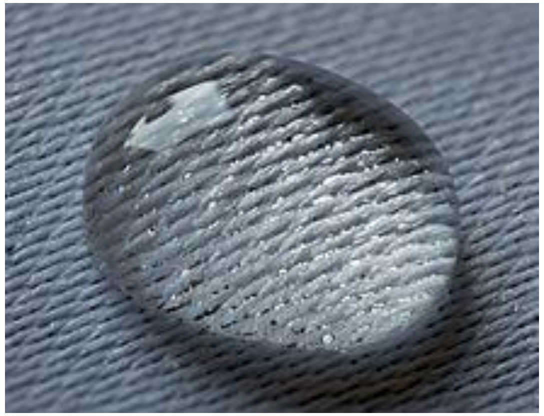
Water Transportation

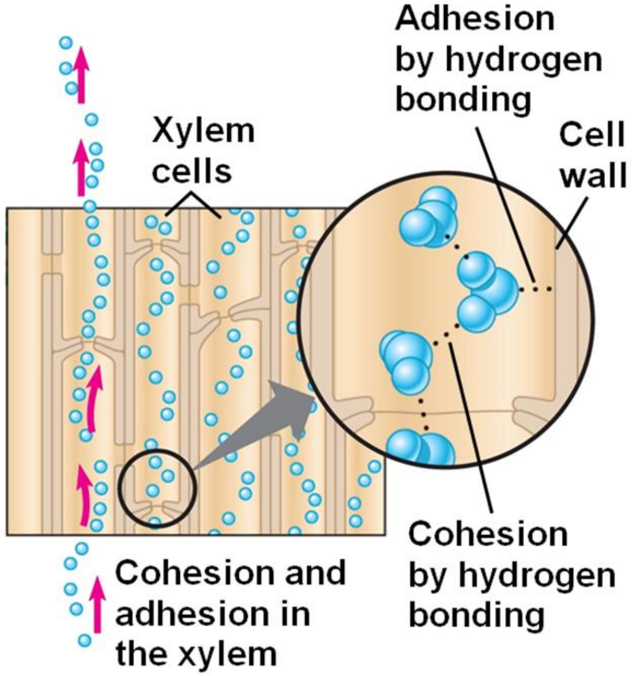
Cohesion-tension Theory

Warming Question

What are **cohesion**, **adhesion** & **surface tension** features of liquid water?

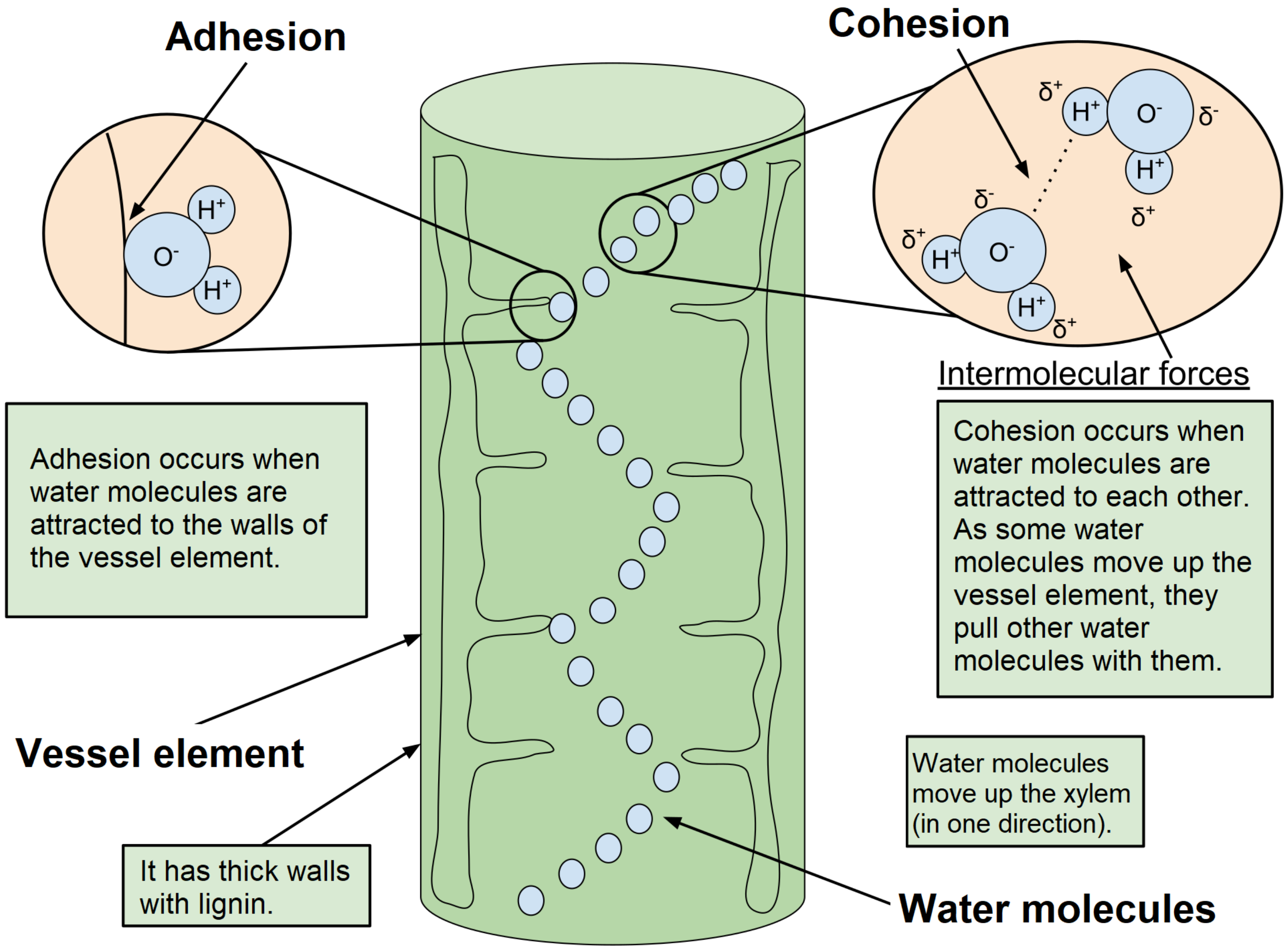


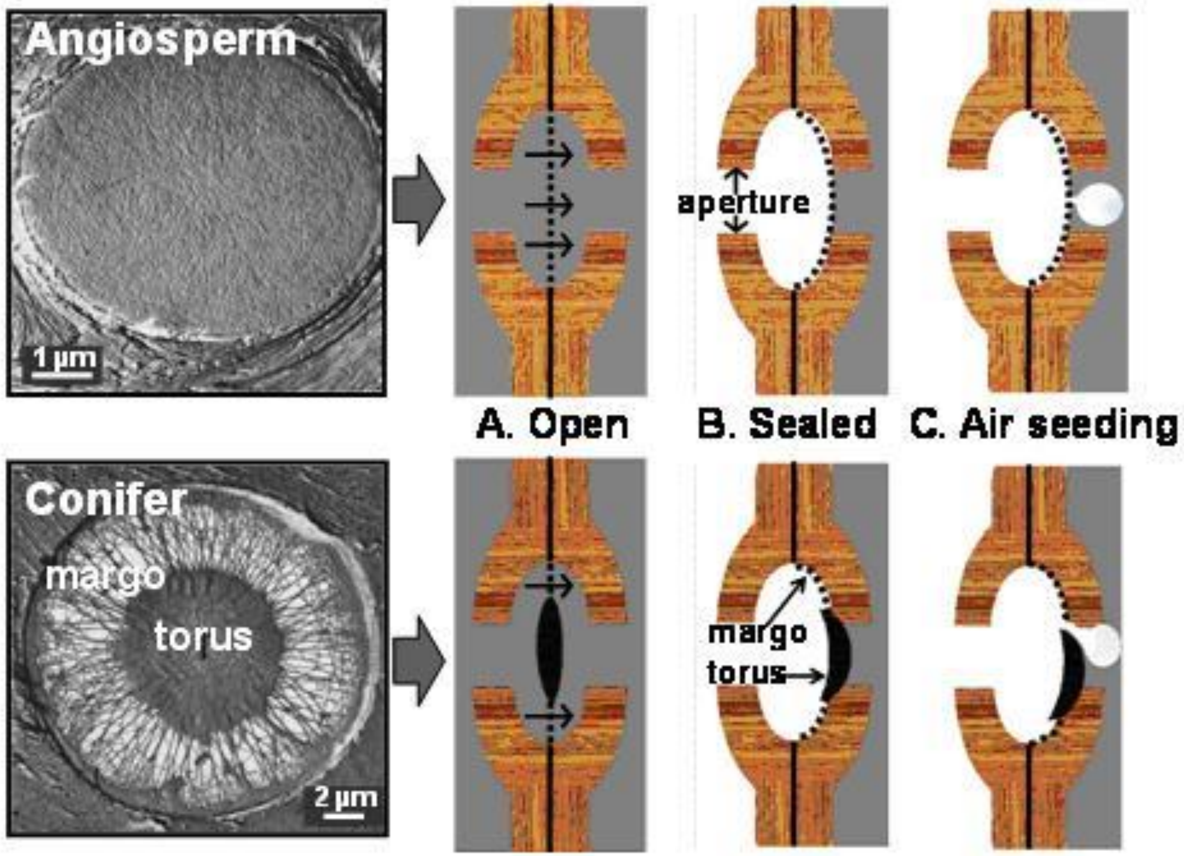


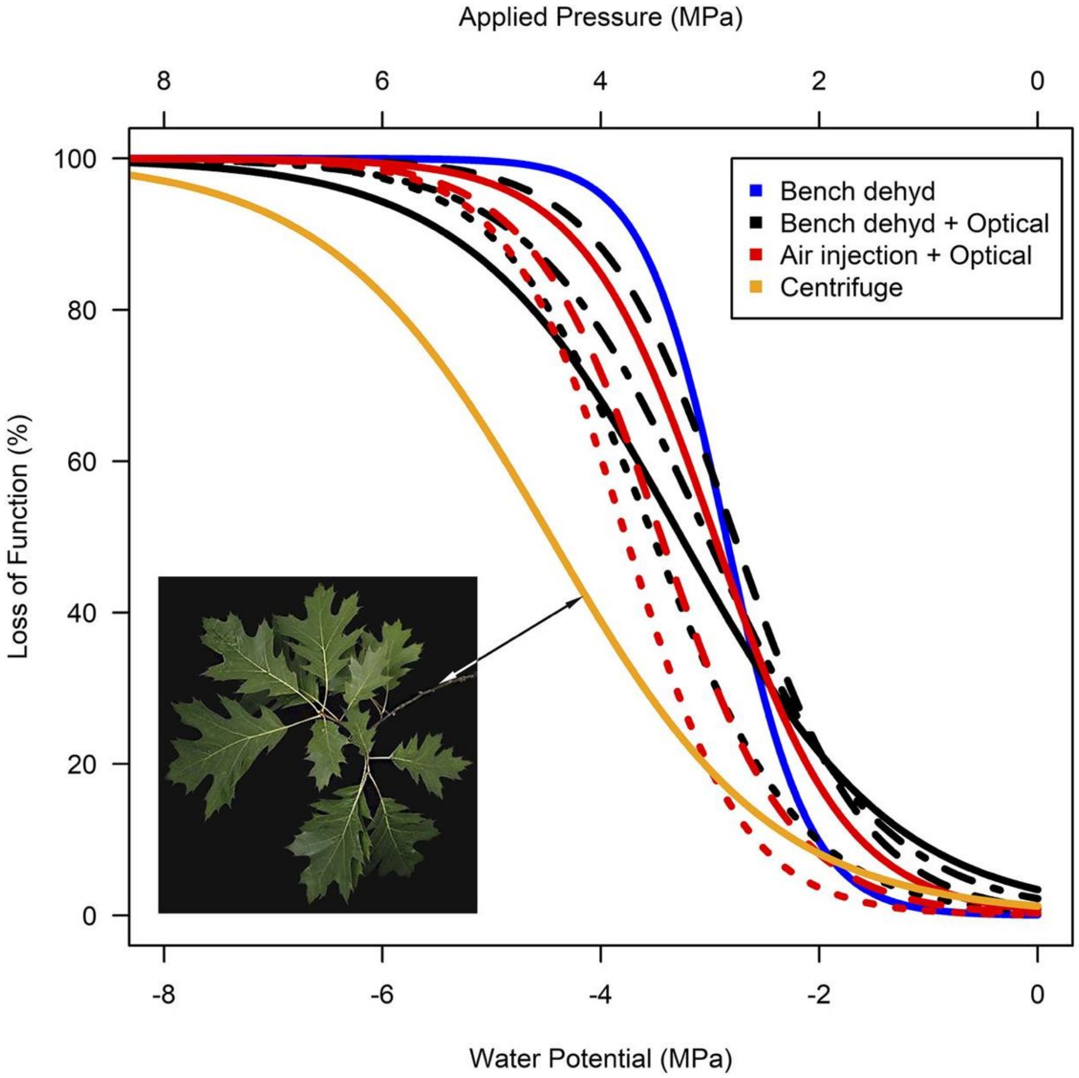


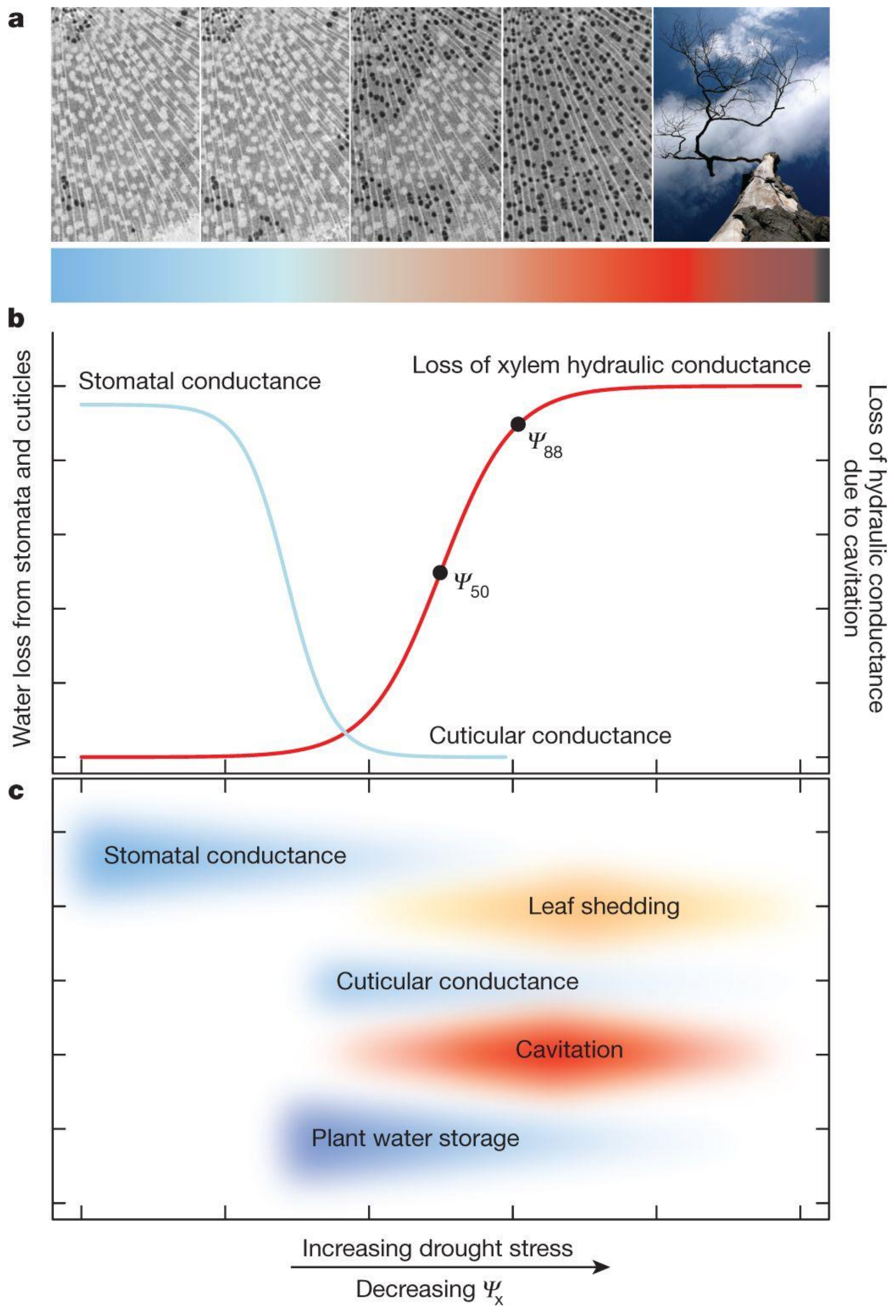
The transpiration-cohesion-tension theory

- **Transpiration (pull):** Evaporation from leaf surfaces generates negative water potential that draws water upward from the roots.
- **Cohesion:** Hydrogen bonding between water molecules maintains a continuous xylem water column.
- **Tension:** Transpiration creates negative pressure in the xylem that pulls the water column upward.
- **Adhesion:** Water molecules adhere to xylem cell walls, stabilizing the column and aiding ascent.



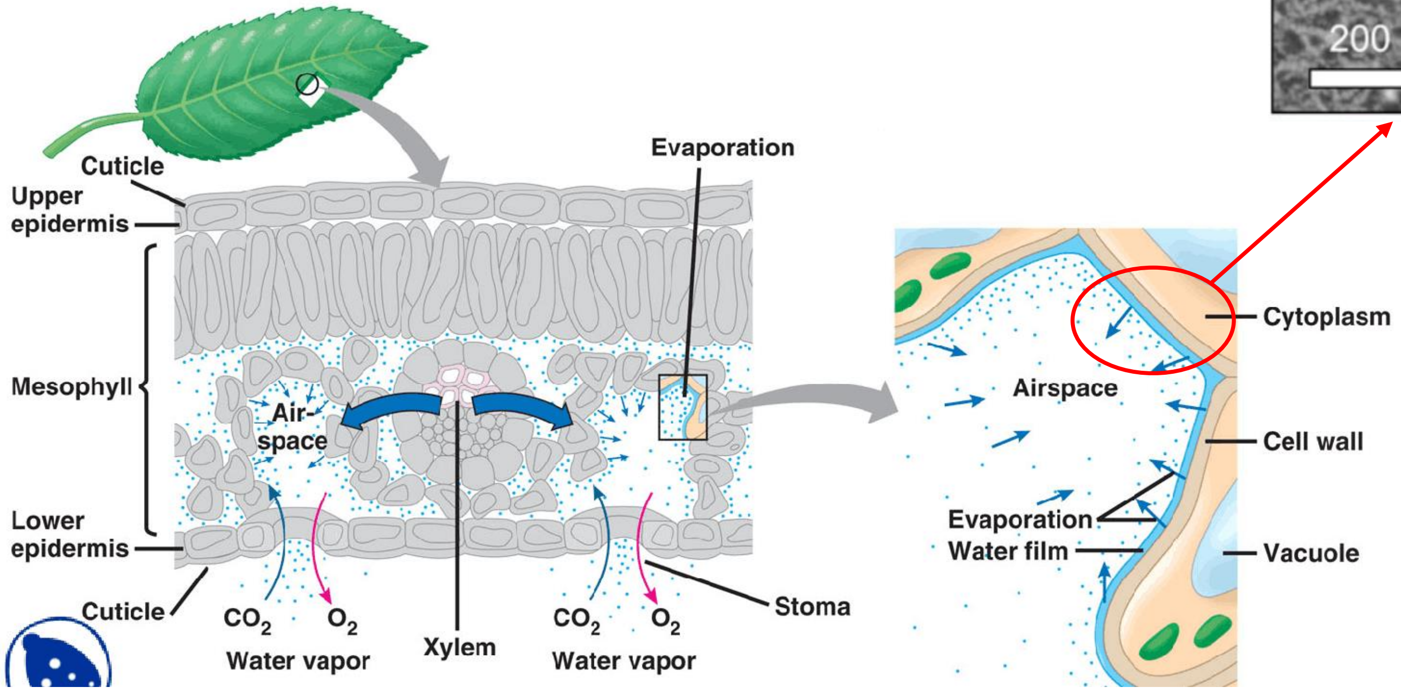

Angiosperm
1 µm
aperture
A. Open
B. Sealed
C. Air seeding
Conifer
margo
torus
2 µm
margo
torus

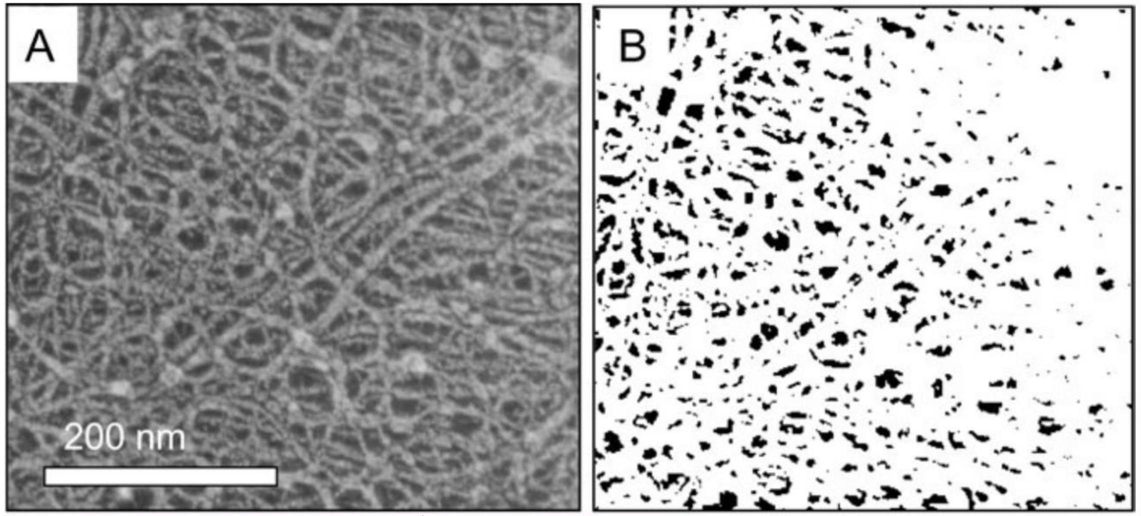

Applied Pressure (MPa)
8
6
4
2
0
100
80
60
40
20
0
Loss of Function (%)
Bench dehyd
Bench dehyd + Optical
Air injection + Optical
Centrifuge
-8
-6
-4
-2
0
Water Potential (MPa)

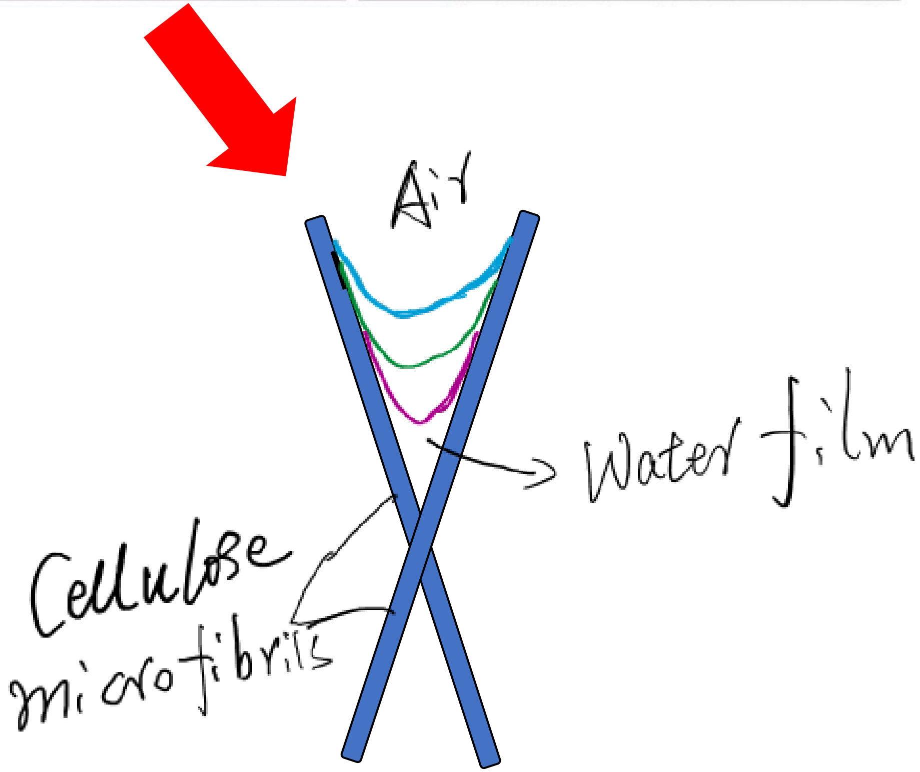


Xylem cavitation (loss of hydraulic) is considered as the major killer.

What Is Transpiration Pull

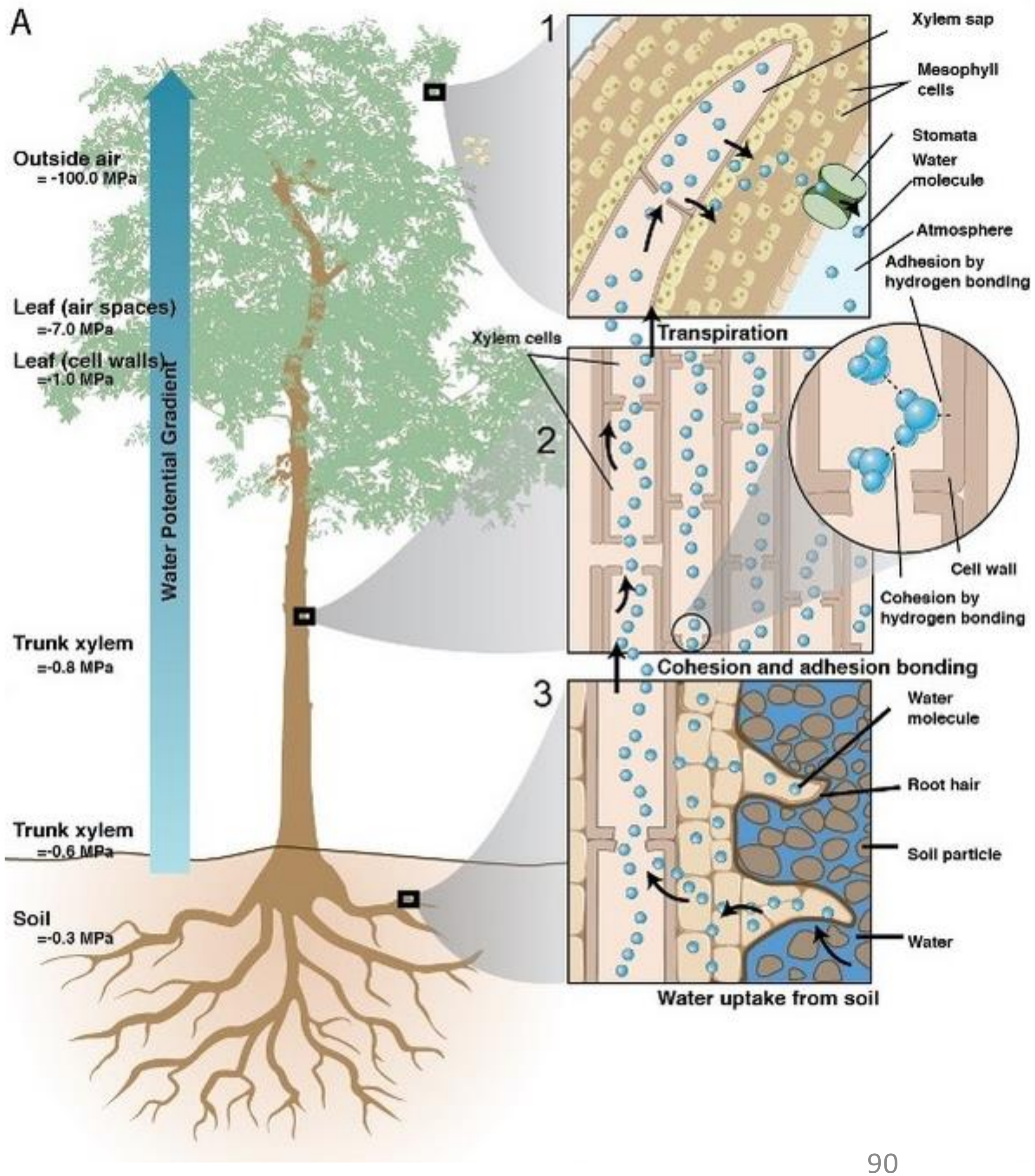






Outline

- Water status of plants
- Availability of water
- Water uptake from soil by roots
- **Water escapes from plants**
- **Water transport through plants**
- **Water Use & Stress**



Water Balance in Plants

Definition: water balance refers to the dynamic equilibrium among water uptake, water utilization, and water loss.

Water uptake > water loss

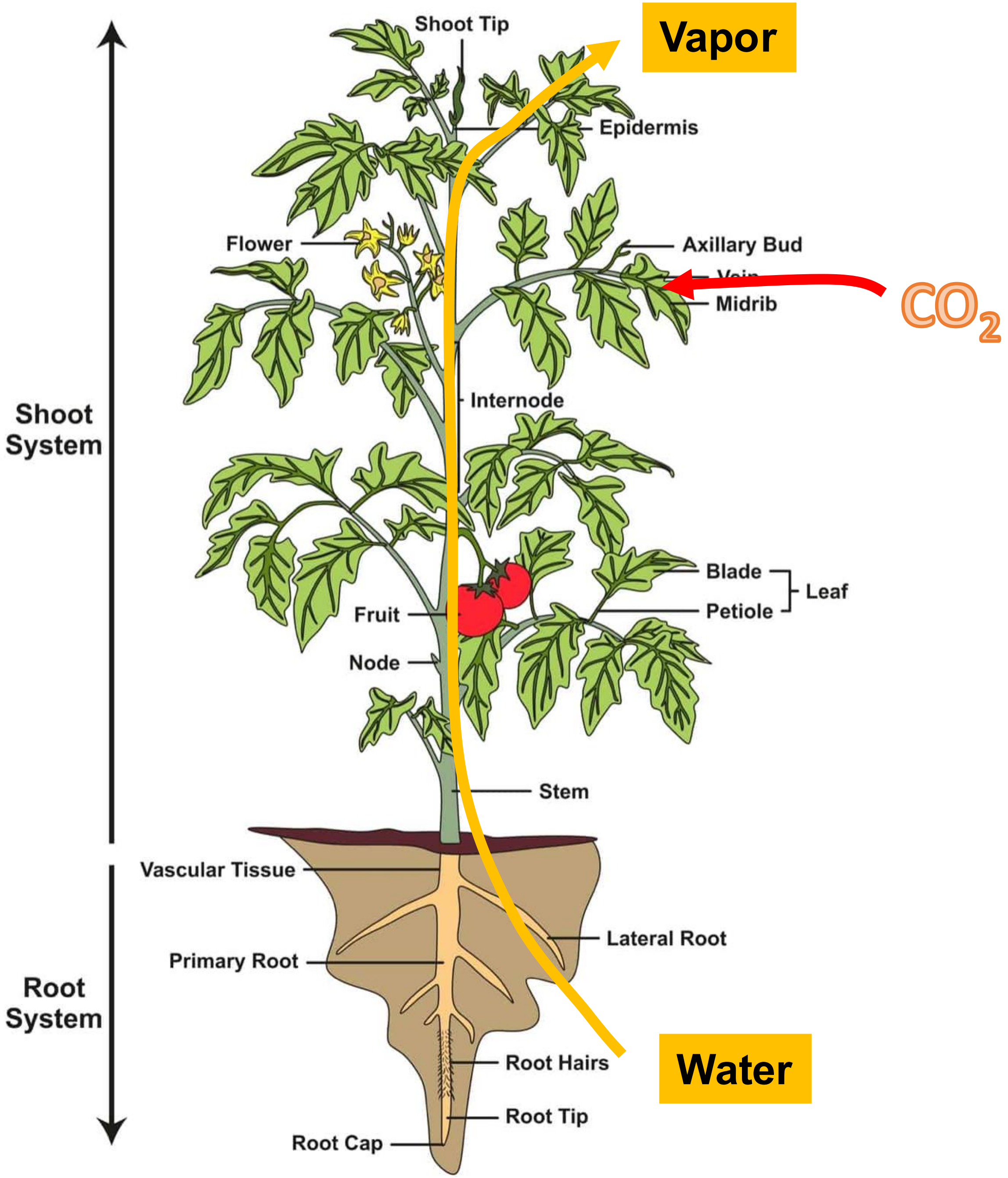
- Guttation may occur.
- Excessive vegetative growth or lodging can result.

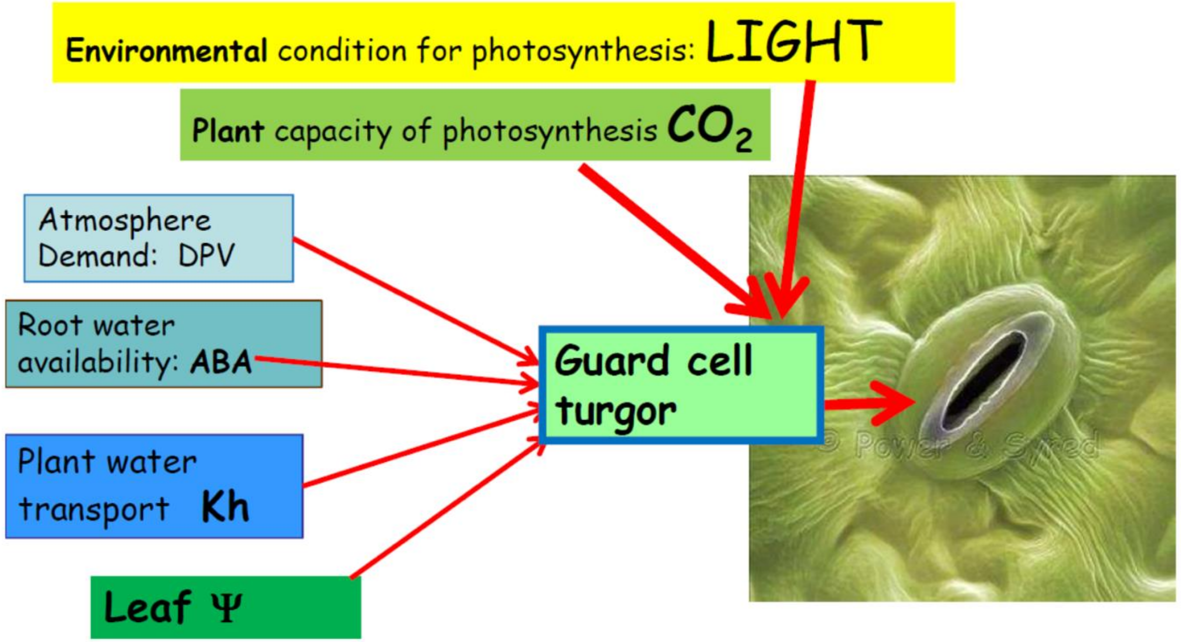
Water uptake < transpiration loss

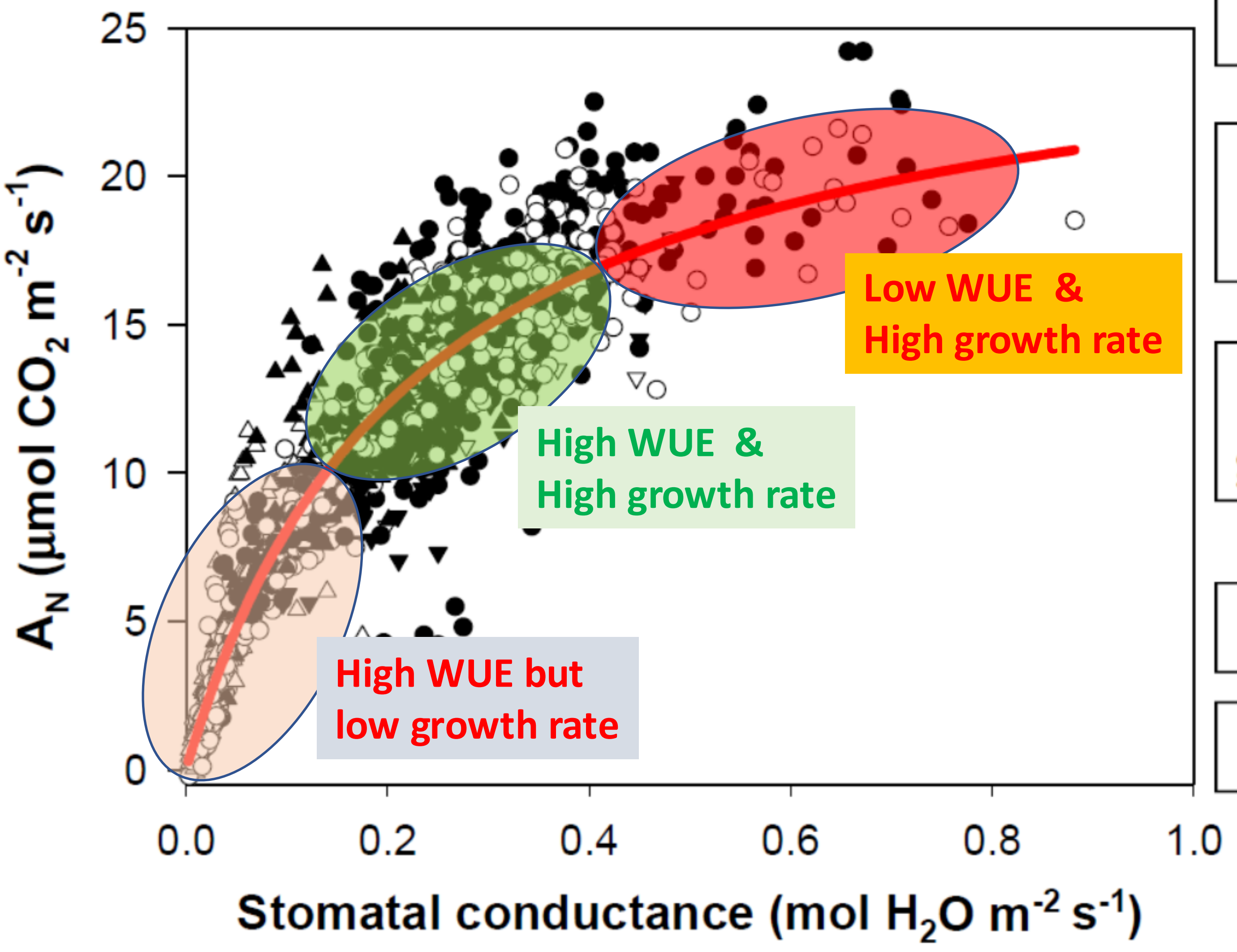
- Reduced tissue water content
- Leaf wilting and drooping
- Suppressed metabolic activity
- Inhibited growth

Water use efficiency

Watershed	Land production	$\frac{Yield}{water\ used}$	Water income
Agriculture	Crop production	$\frac{Yield}{water\ used}$	Crop water use
Plant	Plant production	$\frac{Biomass}{water\ loss}$; ^{13}C	Plant transpiration
Leaf	Leaf photosynthesis	$\frac{Pn}{T_r}$ $\frac{Pn}{g_s}$	Leaf transpiration Stomatal conductance


Shoot System
Root System
Shoot Tip
Vapor
Epidermis
Flower
Axillary Bud
Midrib
CO_2
Internode
Blade
Leaf
Petiole
Fruit
Node
Stem
Vascular Tissue
Lateral Root
Primary Root
Root Hairs
Water
Root Tip
Root Cap


Environmental condition for photosynthesis: LIGHT
Plant capacity of photosynthesis CO_2
Atmosphere Demand: DPV
Root water availability: ABA
Plant water transport Kh
Leaf Ψ
Guard cell turgor
© Power & Syred



10 years

23 grape varieties

Pot and field growing plants

$R^2 = 0.88$

n = 1347

From the water management aspect, high water use efficiency means a relatively high *A* with a relatively low g_s.

Irrigation Indicators

Soil Indicators

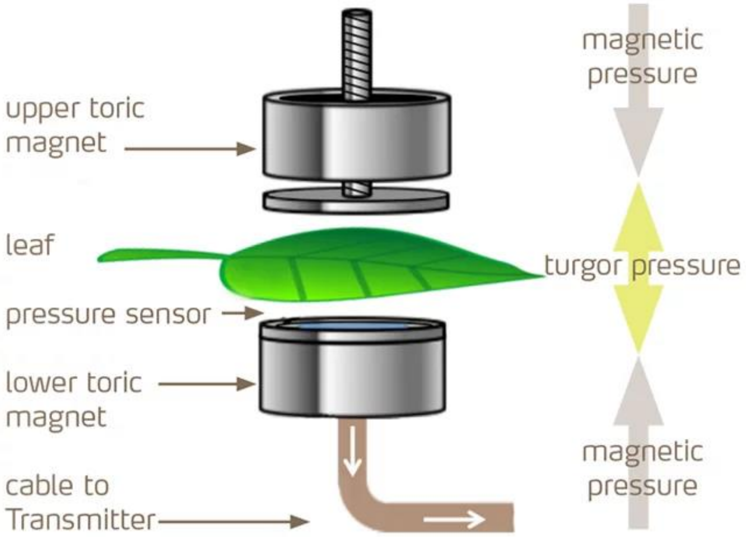
- **Optimal Range:** In the active root zone (0~90cm) required for normal growth, soil moisture should be maintained at **60% ~ 80% of Field Capacity**.
- **Action Rule:** Irrigation should be applied promptly when moisture falls below this threshold.

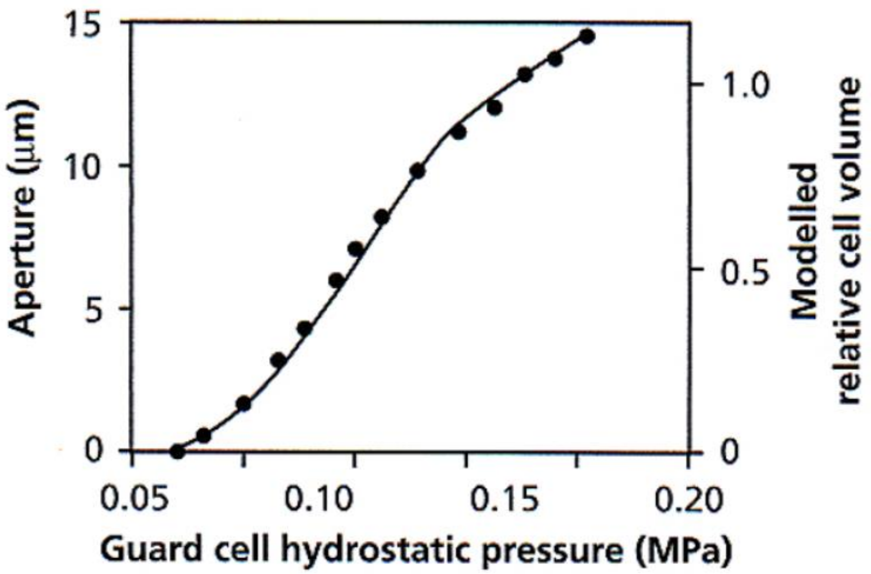
Plant Status

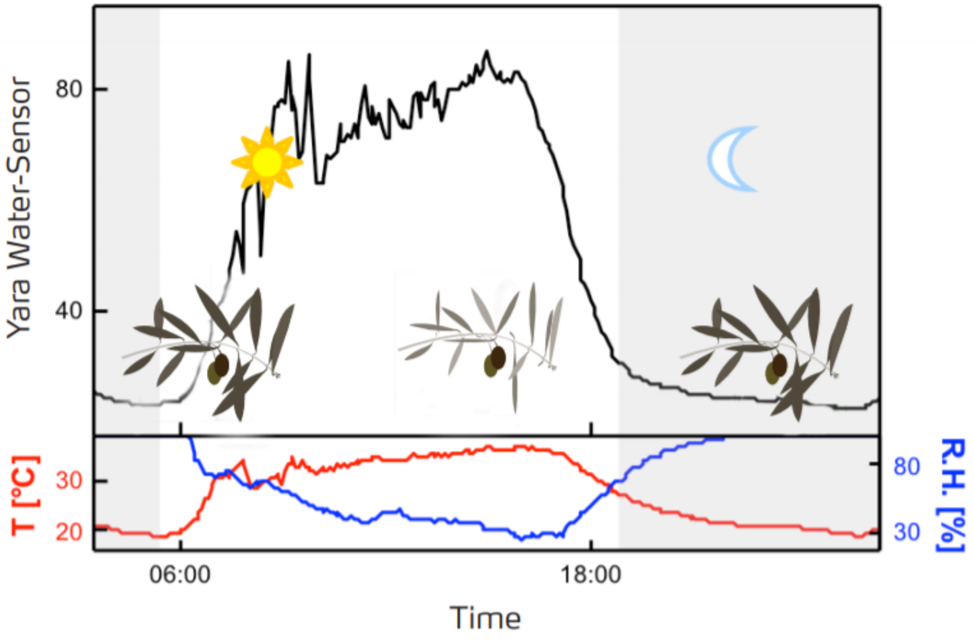
- **Morphological Indicators**
  - ✓ Wilting of young stems and leaves
  - ✓ Noticeable decrease in growth rate.
  - ✓ Stems and leaves occasionally turning red.
- **Physiological Indicators**
  - ✓ Leaf water potential
  - ✓ Cell sap concentration or osmotic potential
  - ✓ Stomatal status (aperture/conductance)

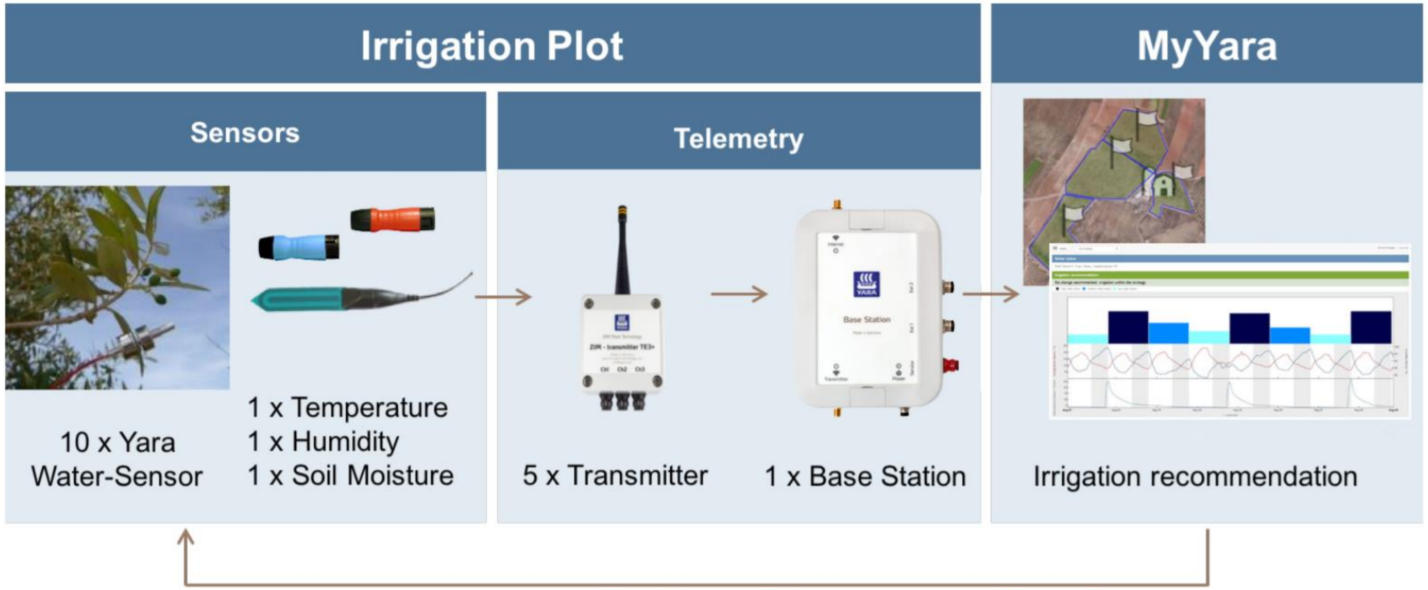
Water Content at Wilting Point (~ -1.5 MPa):

- ✓ **Clay:** 42% water content
- ✓ **Loam:** 24% water content
- ✓ **Fine Sand:** 4% water content

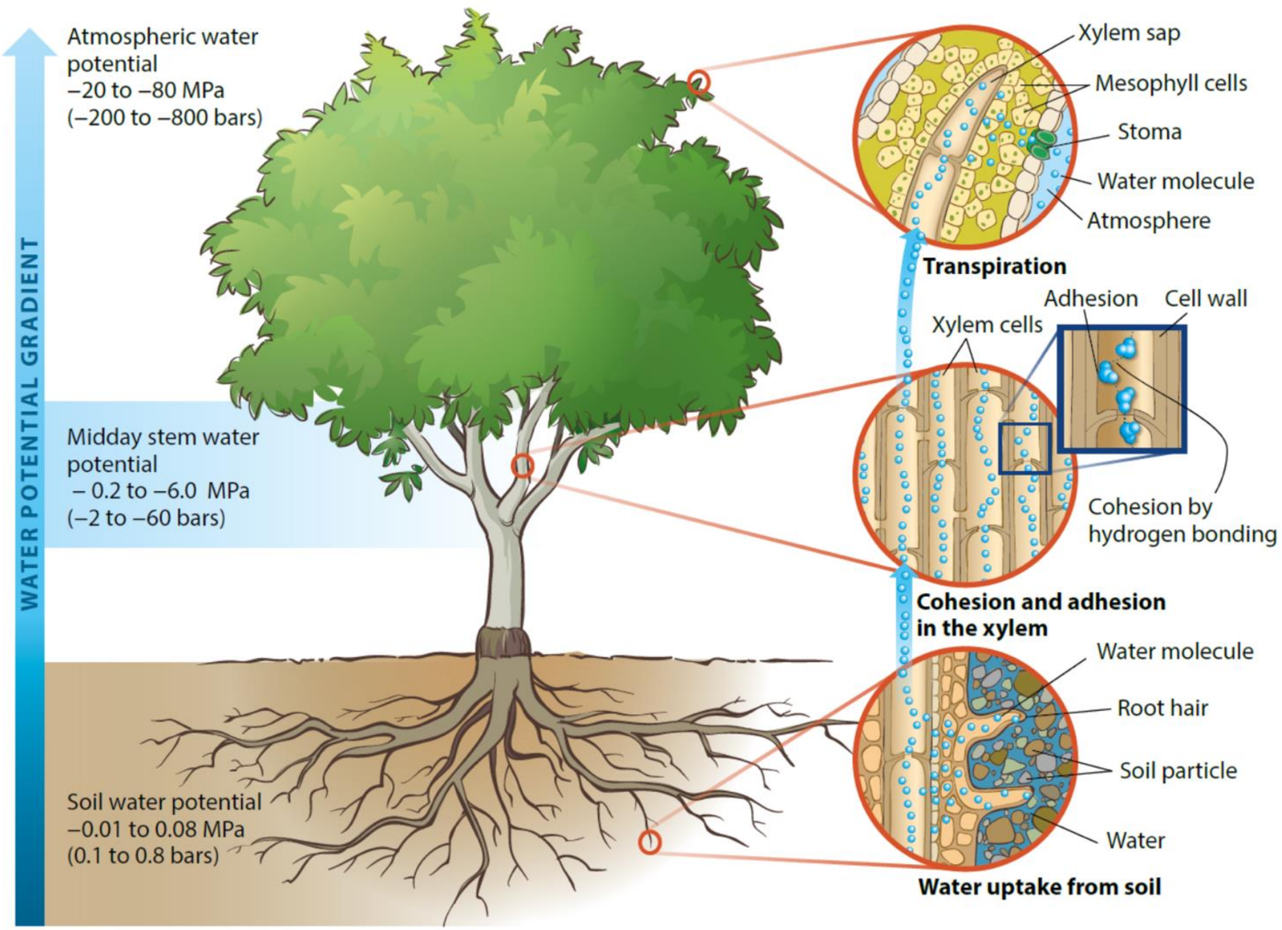


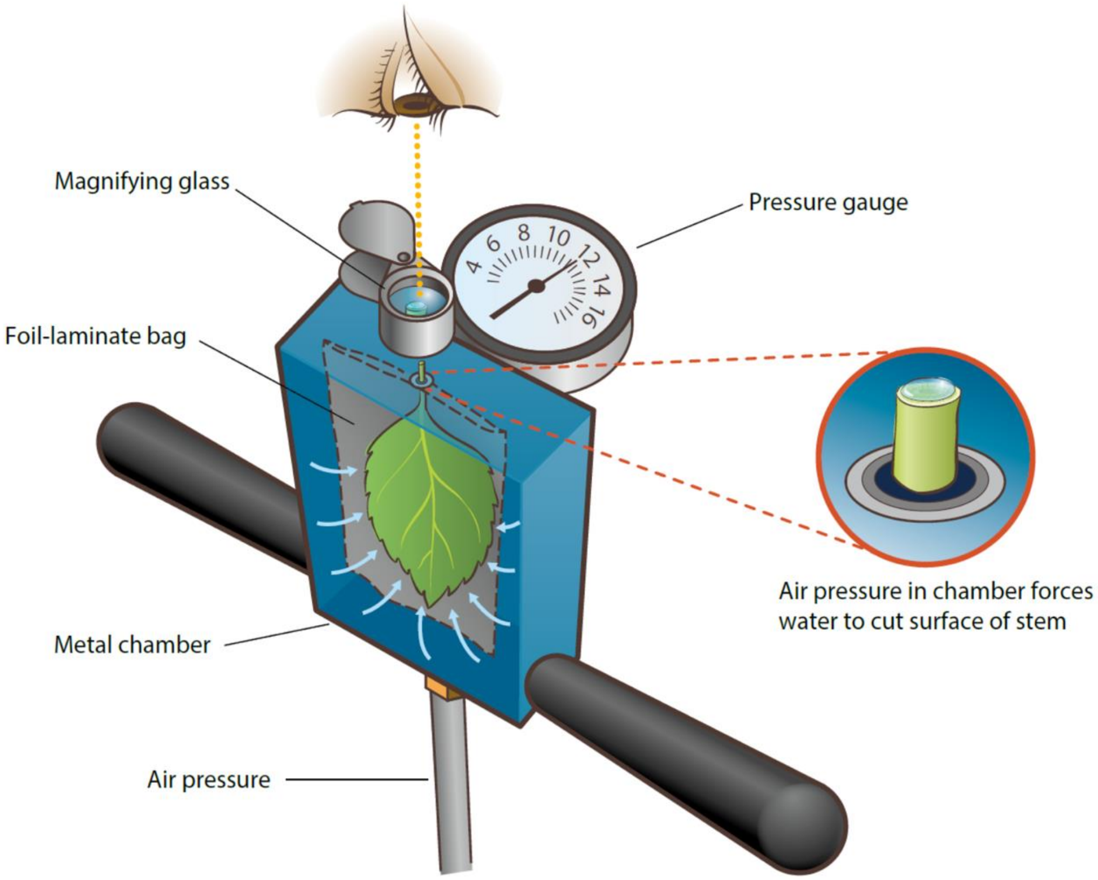






The data are sent wireless to MyYara and the recommendation is available for the farmer.


Atmospheric water potential
−20 to −80 MPa
(−200 to −800 bars)
Midday stem water potential
− 0.2 to −6.0 MPa
(−2 to −60 bars)
Soil water potential
−0.01 to 0.08 MPa
(0.1 to 0.8 bars)
WATER POTENTIAL GRADIENT
Xylem sap
Mesophyll cells
Stoma
Water molecule
Atmosphere
Transpiration
Adhesion
Cell wall
Xylem cells
Cohesion by hydrogen bonding
Cohesion and adhesion in the xylem
Water molecule
Root hair
Soil particle
Water
Water uptake from soil


Magnifying glass
Pressure gauge
Foil-laminate bag
Air pressure in chamber forces water to cut surface of stem
Metal chamber
Air pressure

Critical Period of Water: The developmental stage during which plants are most sensitive to water deficit and most susceptible to yield reduction.

Table 7. Guidelines for interpreting SWP measurements in almond

Pressure chamber reading or SWP measurement (bars)	Extent of crop stress and types of crop responses associated with different SWP levels in almond
0 to −6.0	Not commonly observed in almond.
−6.0 to −10.0	Low stress (when fully irrigated). Stimulates shoot growth, especially in developing orchards. Higher yield potential may be possible if these levels of crop stress are sustained over a season, barring no other limitations related to frost, pollination, diseases, or nutrition. Sustaining these levels may result in higher incidence of disease and reduced life span.
−10.0 to −14.0	Mild stress. Suitable from mid-June until the onset of hull split (July). Still able to produce competitively. Recommended crop stress level after harvest. May reduce energy costs or help cope with drought conditions.
−14.0 to −18.0	Moderate stress. Stops shoot growth in young orchards. Mature almonds can tolerate this level of crop stress during hull split (July/August) and still yield competitively. May help control diseases such as hull rot and alternaria, if present. May expedite hull split and lead to more uniform nut maturity. Also may help reduce energy costs and cope with drought conditions.
−18.0 to −20.0	Moderate to high stress. Should be avoided for extended periods. Likely to reduce yield potential, and may contribute to lower limb dieback.
−20.0 to −30.0	High stress. Wilting observed. Some defoliation. Impacts yield potential.
−30.0 to −60.0	Very high to severe stress. Extensive or complete defoliation is common. Trees may survive despite severe defoliation and may be rejuvenated.
less than −60.0	Trees are likely to die.

Table 10. Guidelines for interpreting SWP measurements in prune

Pressure chamber reading or SWP measurement (bars)	Extent of crop stress and types of crop responses associated with different SWP levels in prune
0 to −6.0	Not commonly observed in prune.
−6.0 to −8.0	Very low stress levels. May occur in March and April. Indicates soil moisture is not limiting. If low crop stress is sustained through the growing season, higher incidence of disease and tree loss may occur.
−8.0 to −12.0	Low to mild stress. Favors rapid shoot growth and fruit sizing in orchards when low to mild crop stress is sustained from April through mid-June.
−12.0 to −16.0	Mild to moderate levels of stress. Appropriate beginning in late June through early August. Rate of shoot growth may be slower but rate of fruit sizing is unaffected. May help manage energy and irrigation costs.
−16.0 to −20.0	Moderate to high crop stress. Rate of shoot growth slows or stops. Should be avoided until fruit sizing is completed in early to mid-August. Once fruit sizing is completed, imposing moderate to high levels of crop stress by reducing irrigation about two weeks before harvest may increase sugar content in fruit and reduce moisture content or "dry-away" (drying costs).
−20.0 to −30.0	High to severe crop stress. More likely to occur in late August and early September, when irrigation is suspended for harvest. Extended periods of high to severe crop stress before harvest results in defoliation and exposure of limbs and fruit to sunburn. May also negatively affect the condition of trees going into dormancy.
less than −30.0	Severe crop stress. Extended periods of severe crop stress should be avoided.

Water footprint of a product

- The **volume** of fresh water used to produce the product, summed over the various steps of the **production chain**.
- When and where the water was used:
  a water footprint includes a **temporal and spatial dimension**.
- Type of water use:
  green, **blue**, **grey** water footprint.

Water footprint of a product

Green water footprint

- volume of rainwater evaporated.

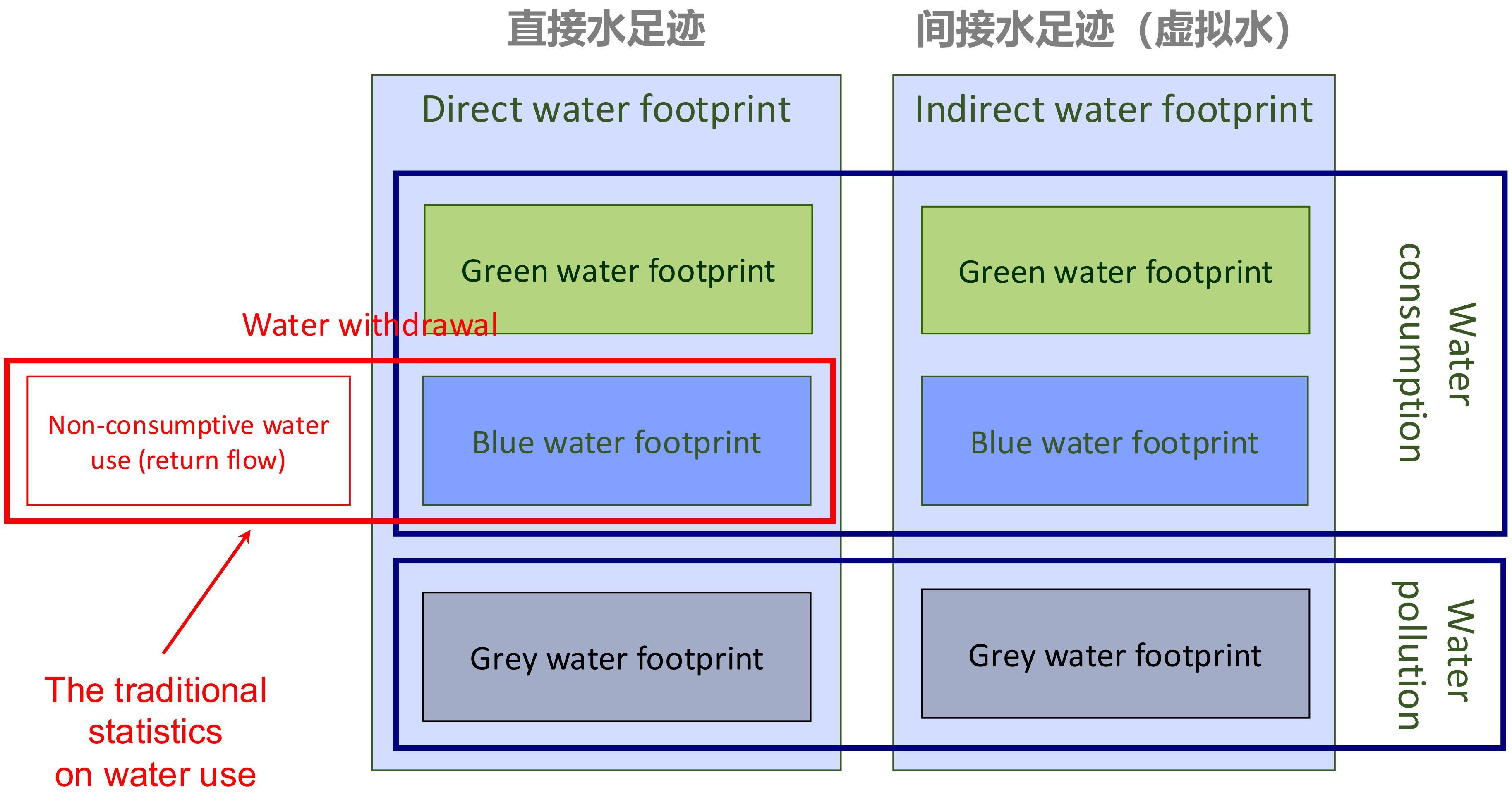
Blue water footprint

- volume of surface or groundwater evaporated.

Grey water footprint

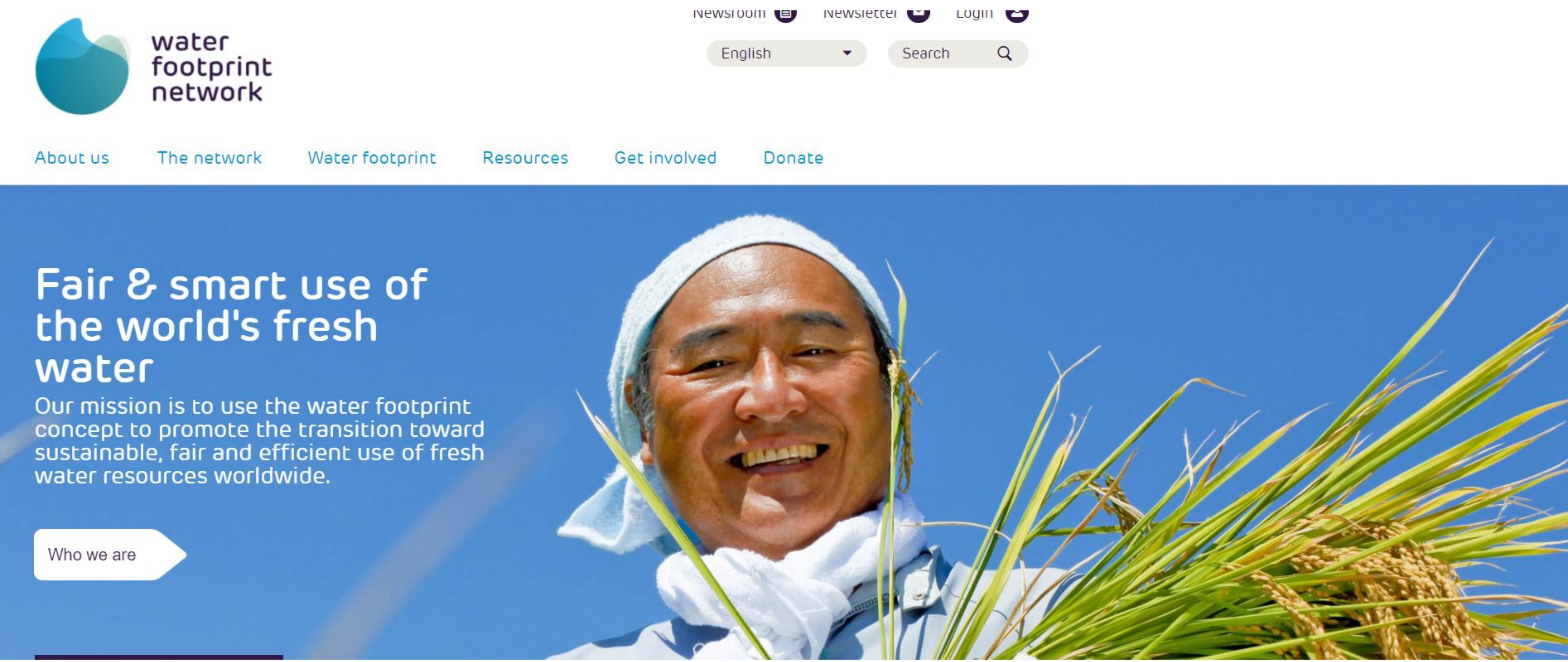
- volume of polluted water.

Components of a water footprint



[Hoekstra, 2008]

For more information: https://waterfootprint.org



Homework Assignments

Scenario A: During a mid-summer heatwave with extremely low humidity an orchard grower notices that an older variety of walnut tree exhibits sudden branch dieback. Measurements show that this older variety has significantly wider xylem vessels compared to a newer, drought-tolerant variety that remained healthy.

- ✓ **Task 1:** Using the cohesion-tension theory, explain the physical phenomenon that likely caused the sudden branch dieback in the older variety under high evaporative demand.
- ✓ **Task 2:** Explain the evolutionary trade-off regarding xylem vessel diameter: why does the newer variety (narrower vessels) have higher resistance to this stress, but potentially lower maximum water transport efficiency under optimal conditions?
- ✓ **Task 3:** Describe how the plant's regulation of stomatal conductance acts as the first line of defense to prevent catastrophic xylem failure under low humidity.

Scenario B: Following continuous heavy rains, a poorly drained section of a soybean field becomes completely waterlogged. Paradoxically, after two days of standing water, the plants in the flooded area begin to wilt severely during the sunny afternoon, exhibiting symptoms identical to drought stress.

- ✓ **Task 1:** Explain this paradox by detailing how soil hypoxia affects root respiration and the gating of aquaporins, ultimately leading to a sharp decrease in root hydraulic conductivity.
- ✓ **Task 2:** Compare the water availability in this flooded scenario to a severe drought scenario. Why do both situations lead to a rapid decline in leaf water potential despite completely opposite soil moisture levels?
- ✓ **Task 3:** If the field is finally drained, will the wilted plants recover their turgor pressure immediately? Justify your answer based on the recovery of root metabolic activity and water transport pathways.

The End

Thanks