

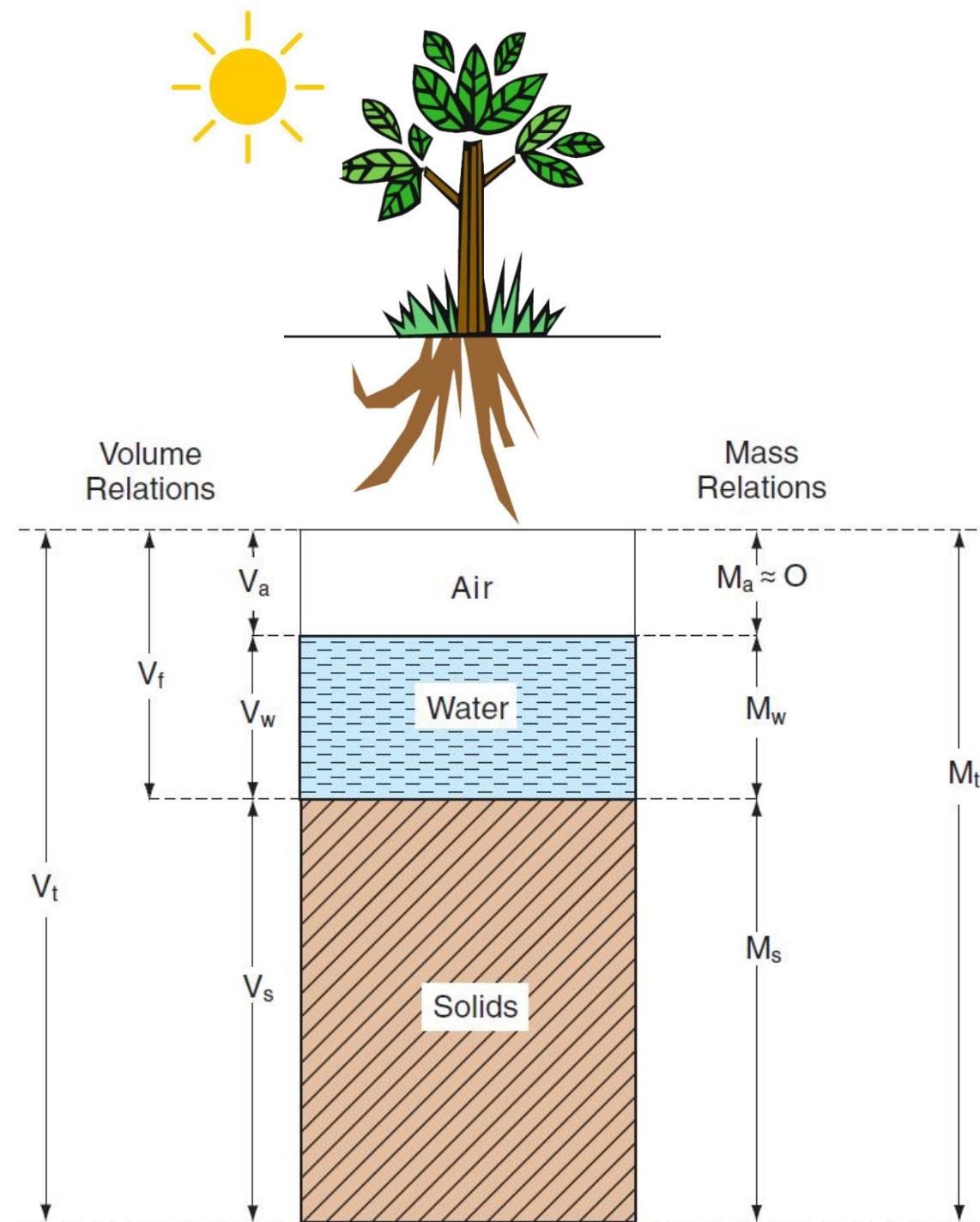
Water in
soil – plant – atmosphere
continuum



Soil – plant – atmosphere

- meteorology
- soil science
- plant physiology (biology)
- hydrology and hydrogeology

different areas of natural sciences, but they are all dealing with water to some extent → scientists share the terminology (properties, variables and factors that affect water movement across geospheres)



Soil – plant – atmosphere

- volume
- mass

- water density (998.2 kg m^{-3})
- viscosity of water (1.0016 milipascalseconds at 20°C)

- pressure
- temperature
- porosity

variability

- surface tension (water/air interface at $20^\circ\text{C} \approx 72.7 \text{ mN m}^{-1}$) and contact angle
- specific heat capacity of water ($4184 \text{ J kg}^{-1} \text{ K}^{-1}$ at 20°C)
- gravitational acceleration g (9.80665 m s^{-2})

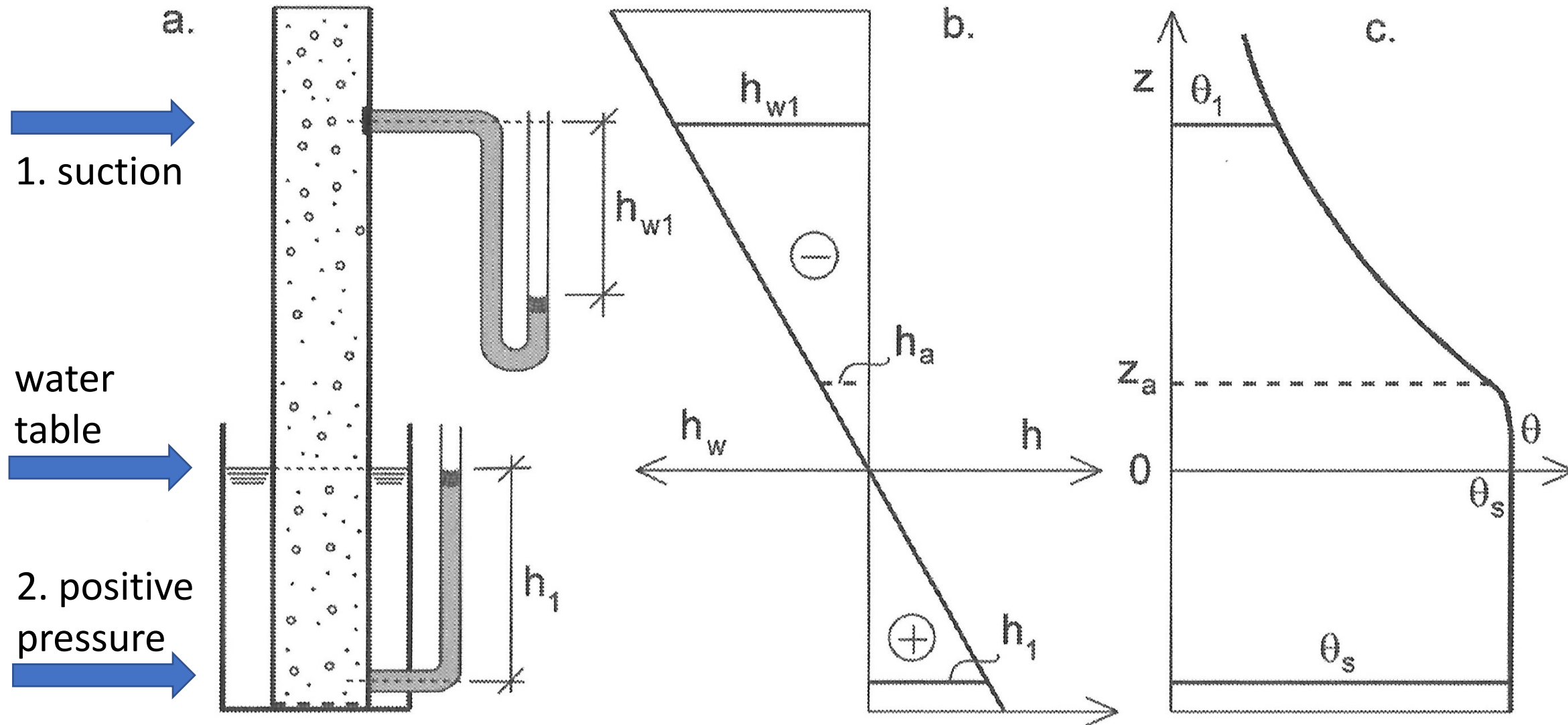
→ some of these properties are (relatively) constant

→ on the other hand, temperature, porosity, pressure or soil moisture are varying in time and space → these differences are creating gradient, which triggers water movement/flow

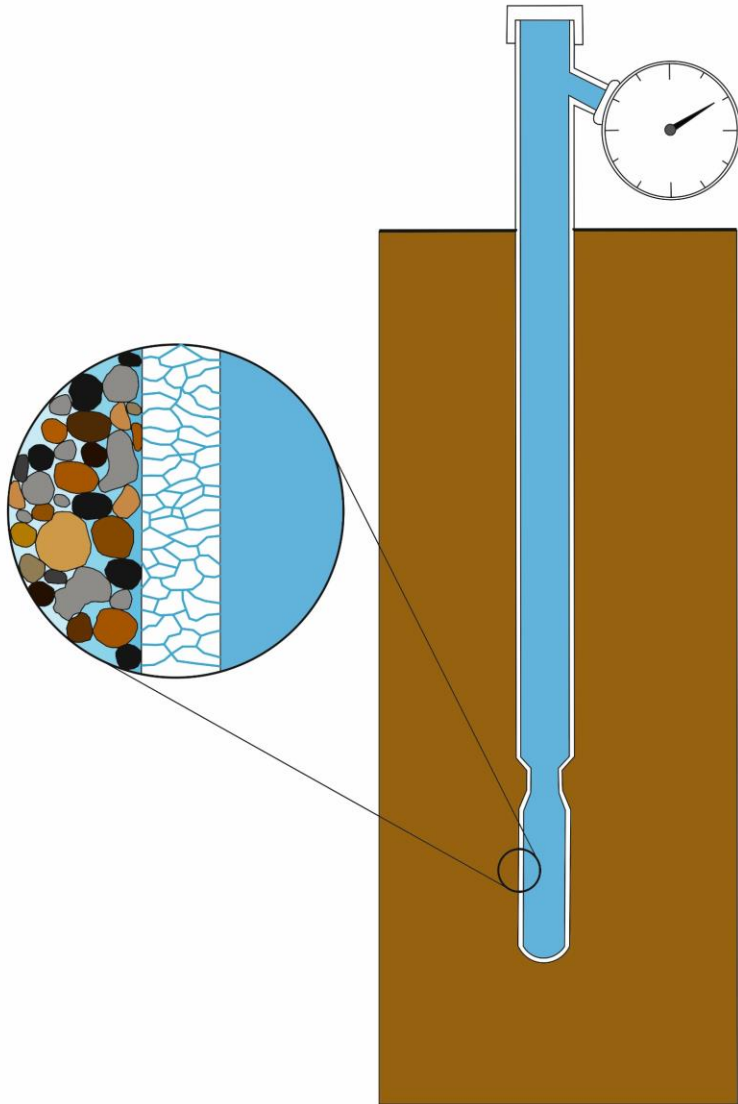
hypothetical soil column

water potential

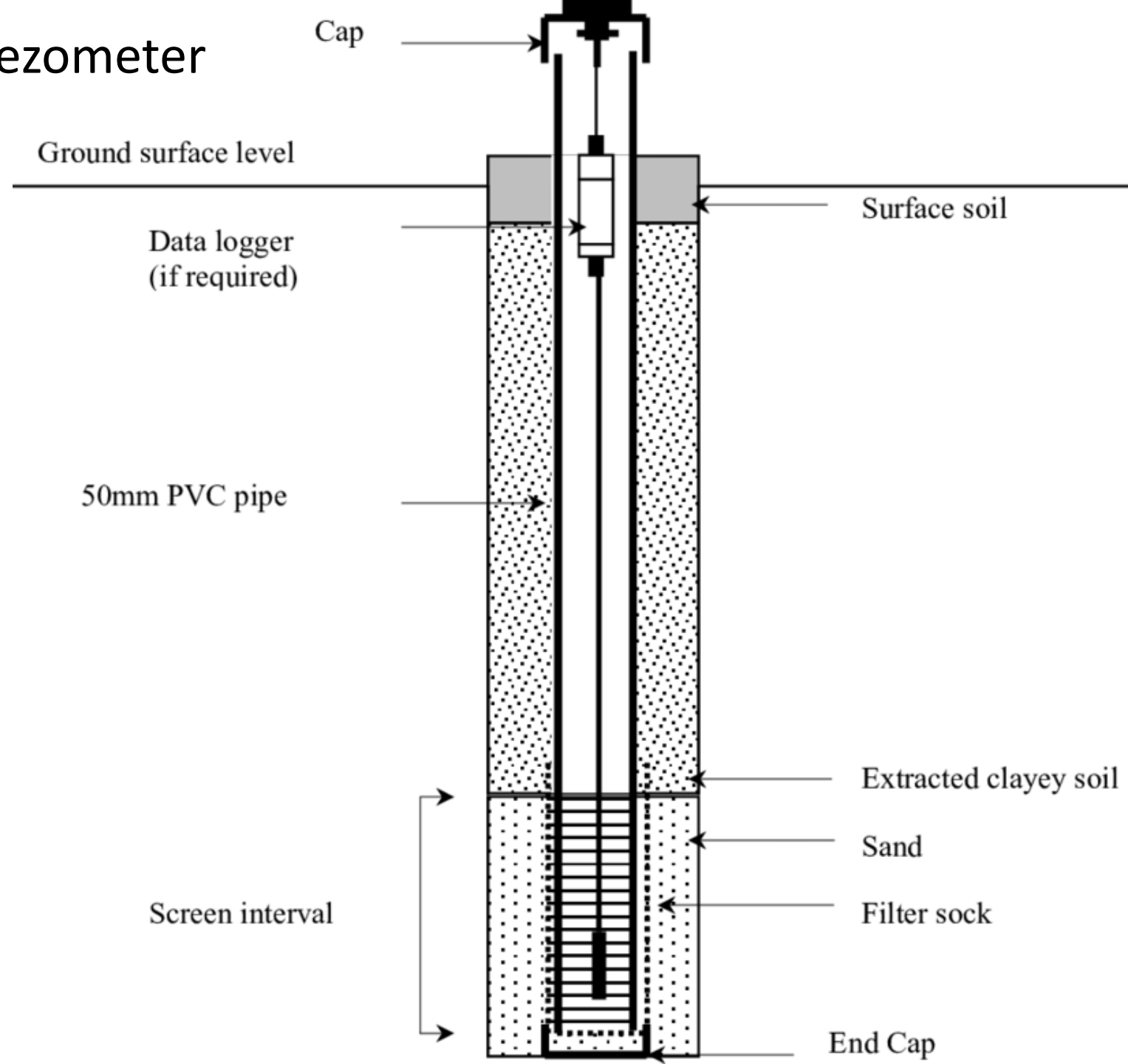
water content



1. tensiometer

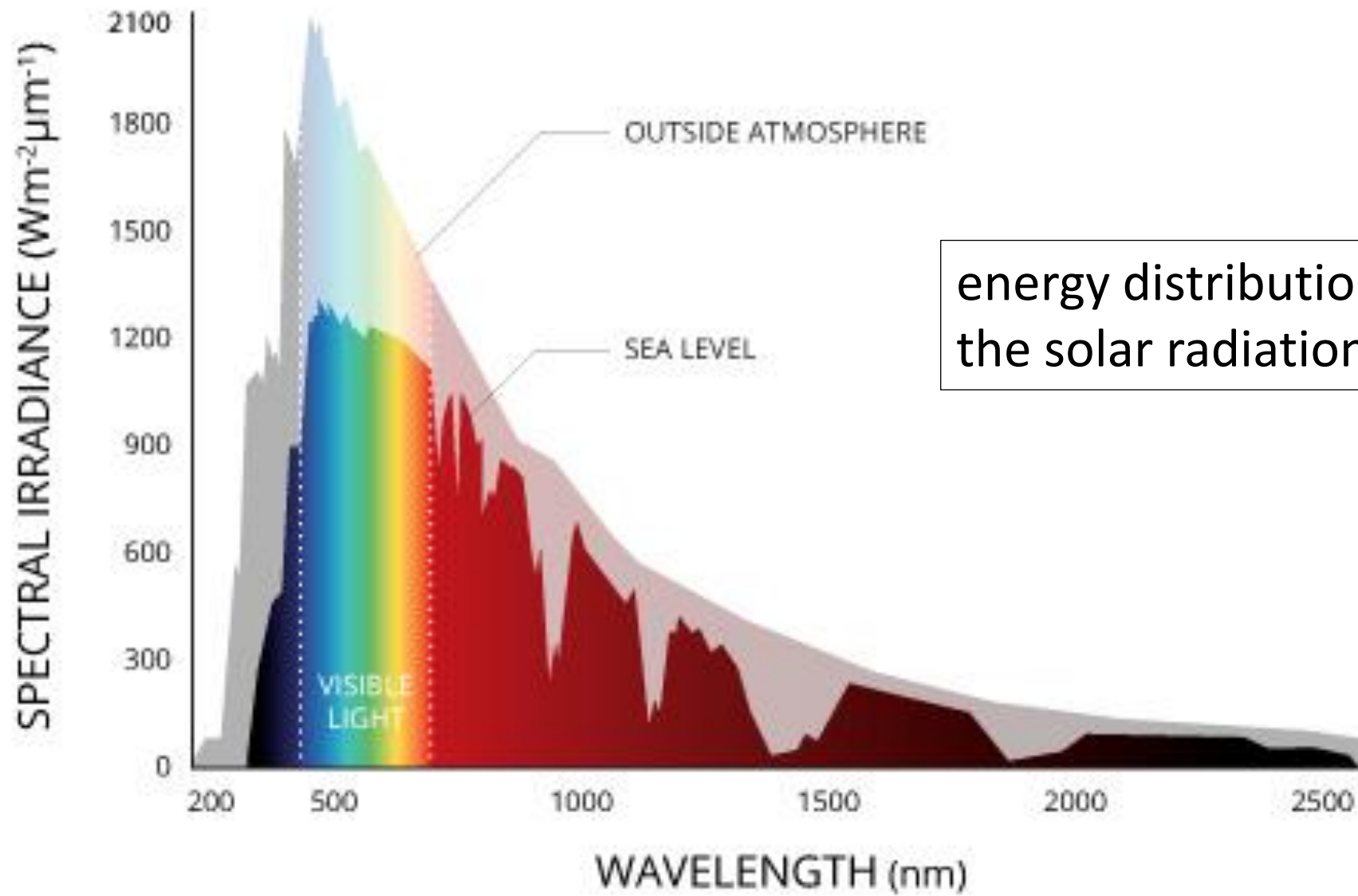


2. piezometer



Water in plant(s)

- **water** is used by plants mainly **for transpiration purpose → cooling**
- photosynthesis is **driven by solar radiation**, more specifically by “**visible light**”; this part of electromagnetic spectrum is **very rich in energy** → the plants need to protect themselves from the heat, while carrying out the photosynthesis. Evaporation is endothermic process → it “consumes” the energy (heat) at plant/atmosphere interface.
- most of the water, which enters the plant is lost relatively quickly through transpiration and **only about 5%** is used in cell expansion and actual growth
- the amount of used water differs, depending on specific plant and water availability: one single irrigated corn plant may use approximately 200 L during summer in Kansas (for example), whereas fully grown tree in tropical rainforest may use > 1000 L per day



energy distribution across
the solar radiation spectrum



In a sense, the plant in the field can be compared to a **wick** in an old-fashioned **kerosene lamp**. Such a wick, its **bottom dipped** into a **reservoir** of fuel while its top is subject to the burning **fire** that **consumes the fuel**, must constantly transmit the liquid from bottom to top under the influence of physical forces imposed on the passive wick by the conditions prevailing at its two ends. Similarly, the plant has its roots in the soil-water reservoir while its leaves are subject to the radiation of the sun and the sweeping action of the wind, which require it to transpire practically unceasingly.

D. Hillel, 2004. Introduction to Environmental Soil Physics.

Water in plant

- leaves (vegetables) 85-95%, xylem parts of stems < 85%, seeds 5-15%
- difference between **poikilohydric** and **homoiohydric** plants: poikilohydric don't have **vacuole** in their cell and may desiccate temporarily without significant harm
- when water content in leaves in most vascular plants decrease < 60% → severe damage
- poikilohydric: algae, cyanobacteria (although their natural habitat is water, they may desiccate for short period of time)
- homoiohydric: higher plants

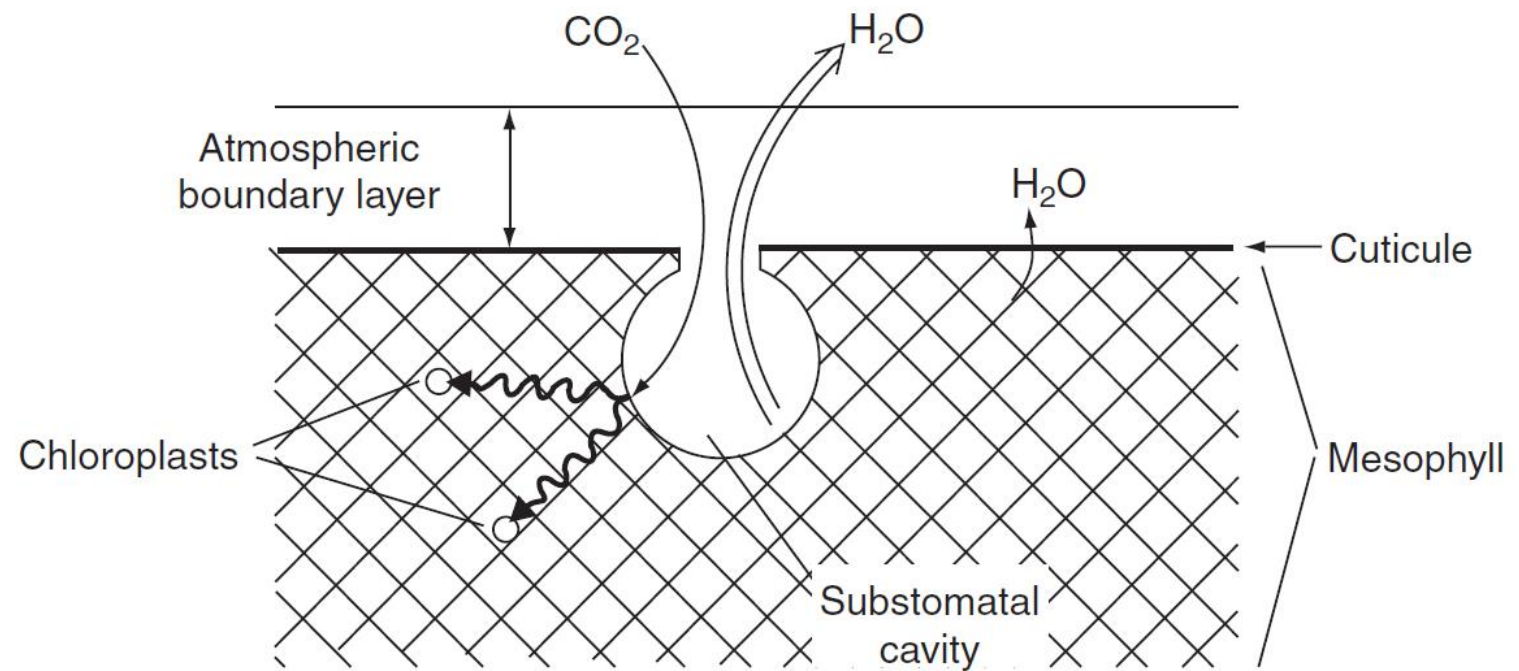
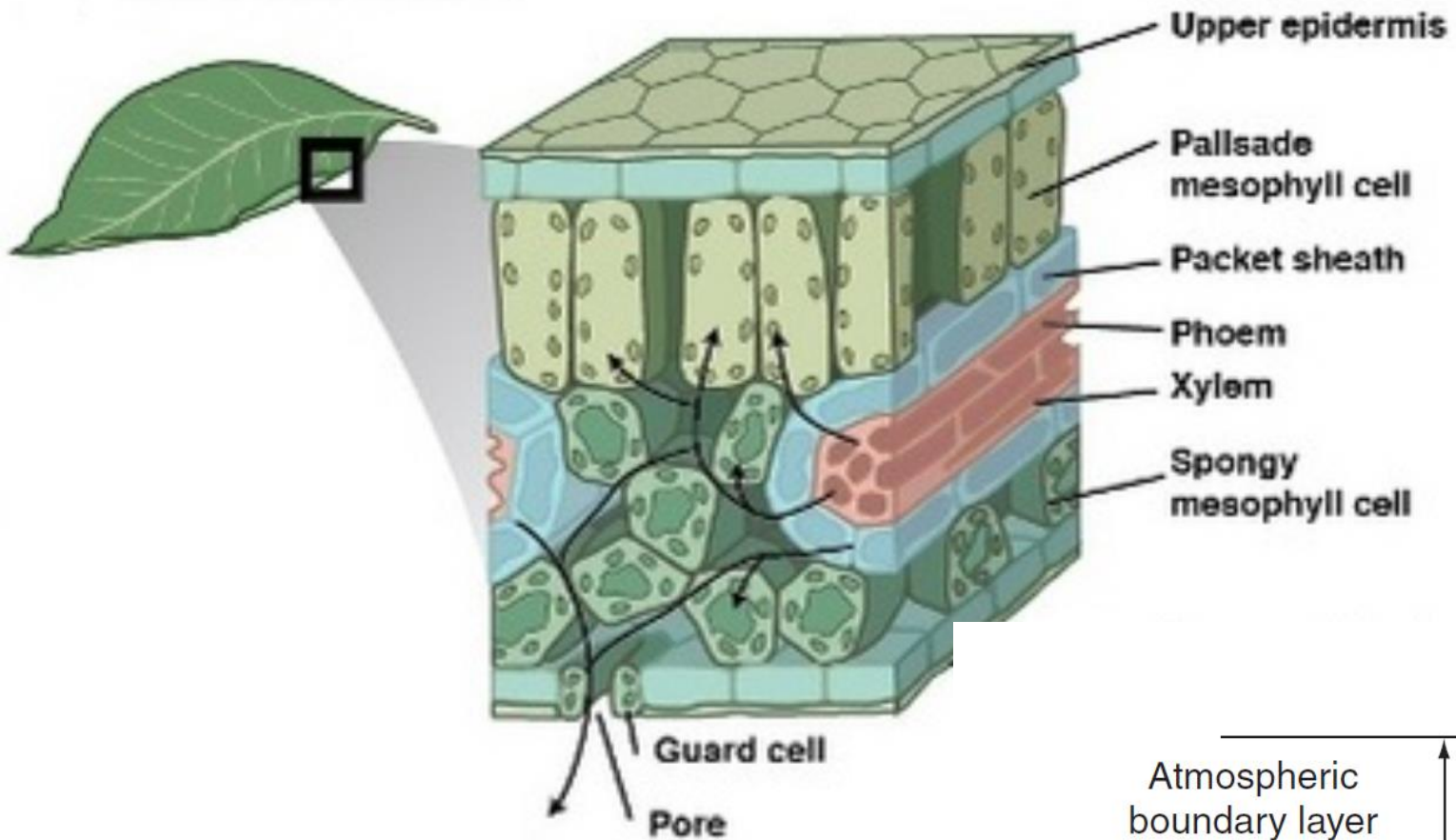
Water properties and transpiration

- **Specific heat capacity** (C_p) of a substance is the heat capacity per mass unit. Liquid water has one of the highest specific heat capacities among common substances, about $4184 \text{ J kg}^{-1} \text{ K}^{-1}$ at 20°C .
- High specific heat capacity of water is beneficial for plants, because it helps them to maintain temperature in the cells and tissues at desired level.
- For the water molecule to be liberated from liquid surface of water body, it needs to overcome intermolecular forces among adjacent molecules. The required energy is called **heat of evaporation** (or enthalpy of vaporization) and in case of water it is 2.257 MJ kg^{-1} .
- High values of these properties makes water **efficient cooling medium** for the plants.

Transpiration

- Photosynthesis is dependent on sunlight and transpiration
- The plants are not strictly passive when it comes to transpiration. Through stomata plants partially regulate the amount of transpired water.
- Besides reducing the transpiration, closing the stomata will limit CO₂ intake, that inherently slower down the photosynthesis.
- Decrease in transpiration results in overheating and the plant reacts by respiration (instead of photosynthesis)
- Apart from stomata action, the plant react on changing soil moisture through other adaptation mechanisms as well. For example, by length of root system, or by root/ shoot ratio.

Leaf Cross Section

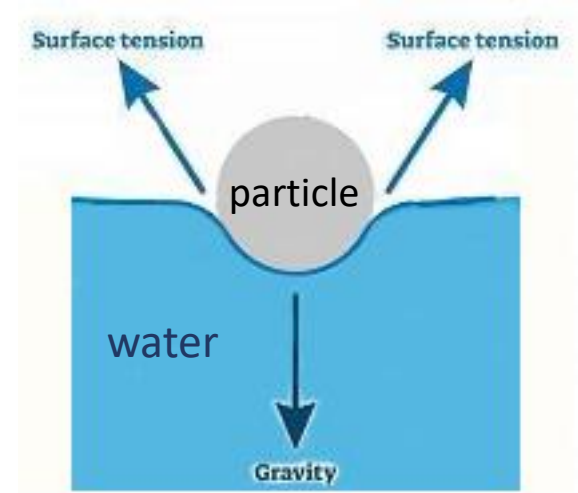


Water (cohesion)

- Due to the high polarity are water molecules attracted by greater force at the water/air interface towards the liquid in comparison to air.
- An increase in water surface requires a transfer of water molecules from inner part of given volume towards the surface and at the same time disruption of hydrogen bonds between the molecules. That requires work. Opposite process – decreasing of surface area of water volume is spontaneous and is accompanied by creation of new hydrogen bonds due to cohesive forces between water molecules.
- When the effect of gravity is small, the water will form spheric shape. Under natural conditions only small volumes of water form spherical shapes, for example when they are place onto hydrophobic surface.
- Cohesive forces are causing surface tension, which is partially responsible for capillary elevation (Δh).

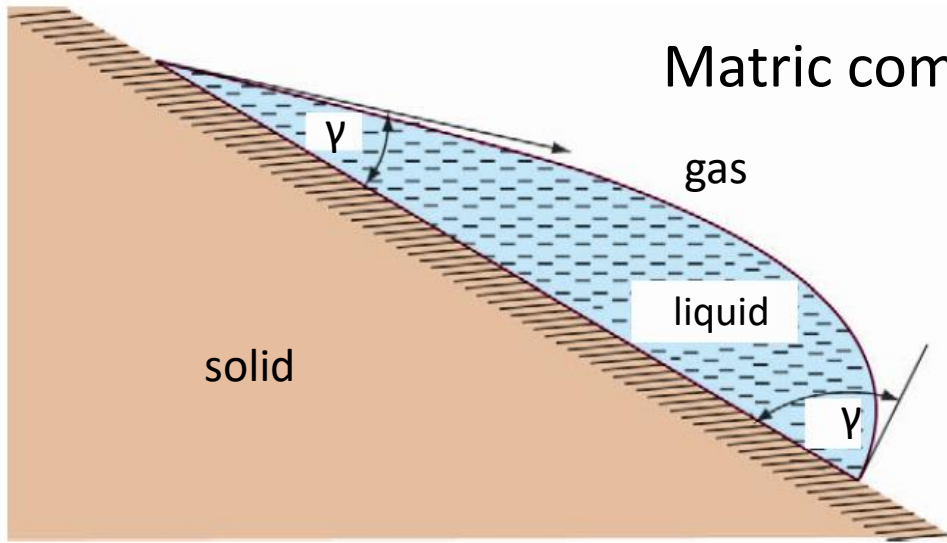
Water (cohesion → surface tension)

- Surface tension (σ_{LG}) is a force acting along a line of unit length parallel to the surface, but perpendicular to the line.
- Molecules below the surface of a liquid are influenced by intermolecular attractions from all directions. Those on the surface are attracted only toward the interior. These attractions pull the surface layer toward the center. The most stable situation is one in which the surface area is minimal. For a given volume, a sphere has the least possible surface area, so drops of liquid tend to assume spherical shapes. Surface tension is a measure of the inward forces that must be overcome to expand the surface area of a liquid.

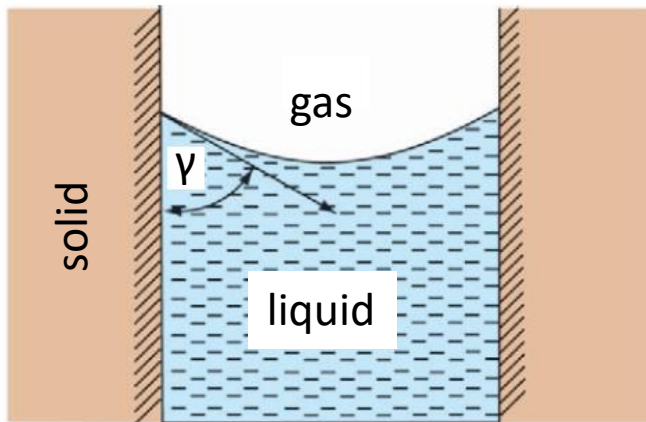


Matric component of water potential

$$\Psi_T = \Psi_m + \Psi_s + \Psi_p + \Psi_z$$



is controlled by geometry of pore system and contact angle formed at solid/air/water interface



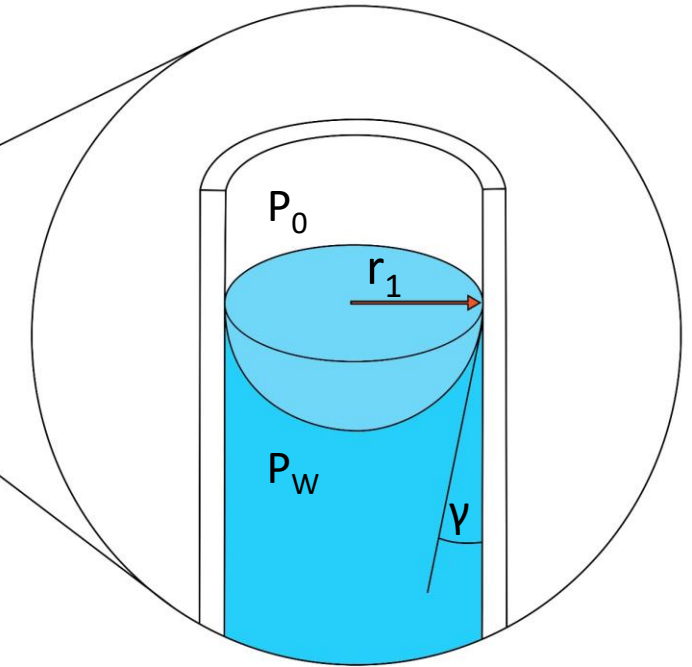
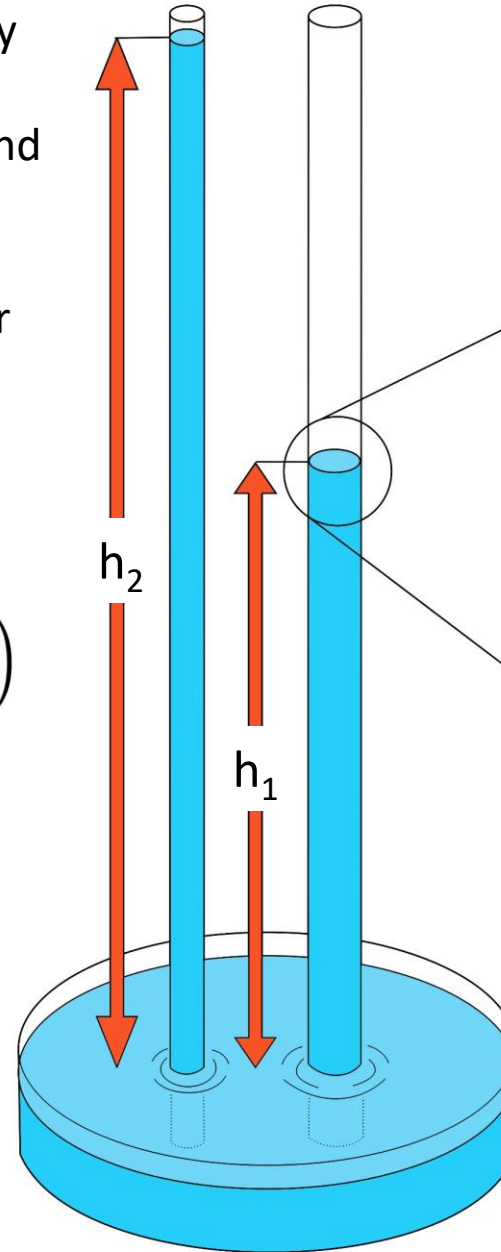
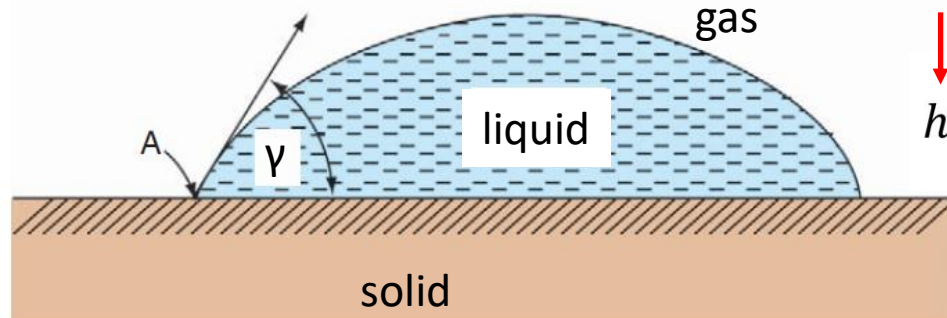
contact angle

$$\cos \gamma = \left(\frac{\sigma_{GS} - \sigma_{SL}}{\sigma_{LG}} \right)$$

$$h = \frac{2\sigma \cos \gamma}{\rho_w g r}$$

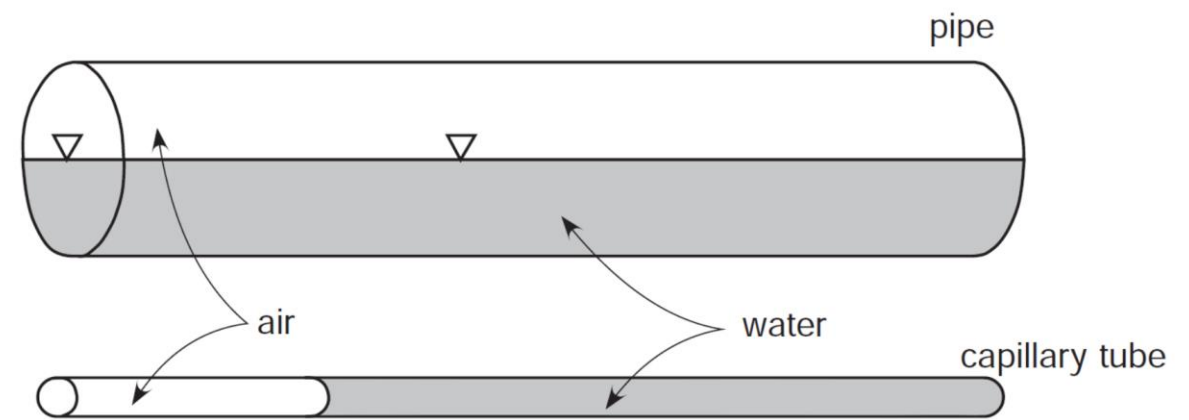
capillary elevation

$$h(m) = \frac{14.84}{r(\mu m)}$$



$$\begin{matrix} r_2 < r_1 \\ h_2 > h_1 \end{matrix}$$

Water (capillary elevation)



- in fine pores with diameter < 0.1 mm capillary forces affect water movement;
- at the solid/liquid/air interface the meniscus with a contact angle γ is formed.

$\gamma < 90^\circ \rightarrow$ concave meniscus

$\gamma > 90^\circ \rightarrow$ convex meniscus

- if the $\gamma \approx 0$ water in the capillary will rise (h) depending on the diameter, d (or radius, r) of the capillary

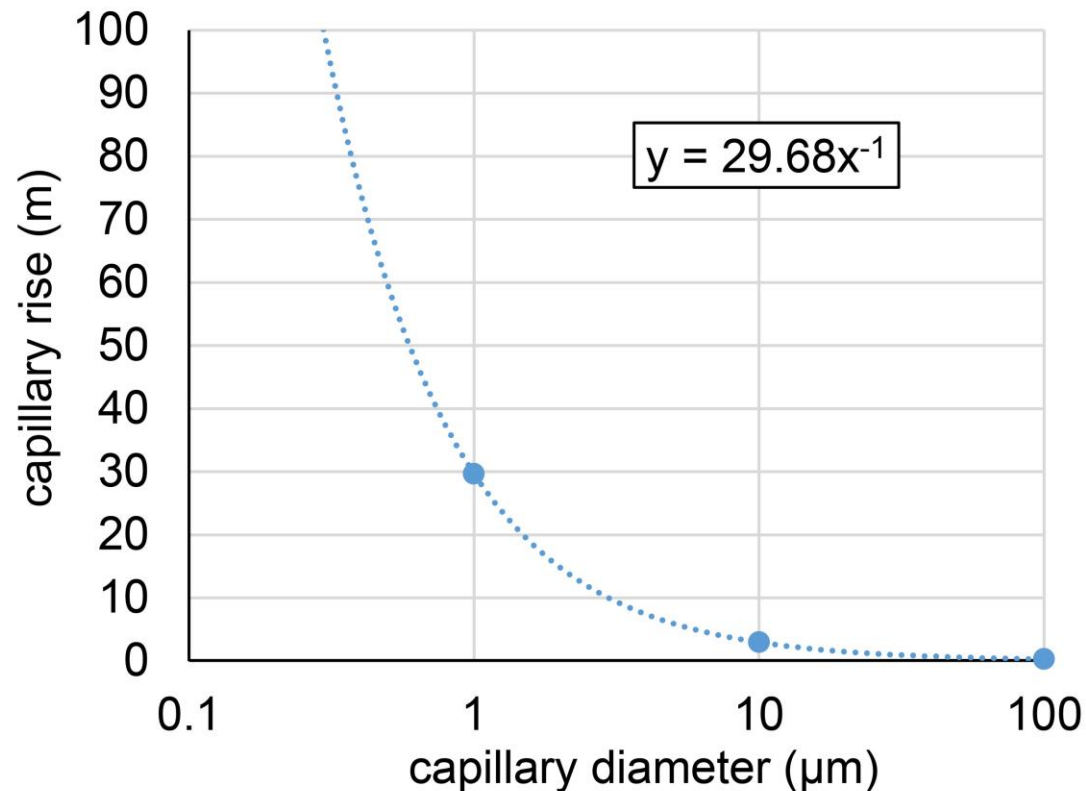
$$h = \frac{2\sigma}{r\rho g} = \frac{4\sigma}{d\rho g}$$

$$h(\text{m}) = \frac{14.84}{r(\mu\text{m})}$$

$$h(\text{m}) = \frac{29.68}{d(\mu\text{m})}$$

Water (capillary elevation)

- in fine pores with diameter < 0.1 mm capillary forces affect water movement; if contact angle $\gamma \approx 0$ (at liquid/solid interface), water in the capillary will rise (h) depending on the diameter (d) of the capillary



Capillary elevation in plants

- there are **two** different groups of **vascular tissues** that are involved in the process of transportation: **xylem** carries mainly water and minerals from the roots to the leaves, whereas **phloem** carries the organic assimilates synthesized by leaf
- xylem begins as a series of living cells but as they mature the cells commit suicide (referred to as programmed cell death), they **lose their cellular contents** and form **hollow** tubes
- there are two kinds of conducting elements (i.e., transport tubes) found in the xylem:
 - 1) **tracheids** - smaller diameter and length
 - 2) **vessels** - consist of individual cells, diameter app. 50 μm , length usually around 5 cm, but in some plants, they may be several meters long
- capillaries in xylem have diameter of 50 to 100 μm (capillary rise 60, 30 cm), but there are also smaller ones with $d \leq 0.1 \mu\text{m}$ that help to elevate the water

Water flow through the plants

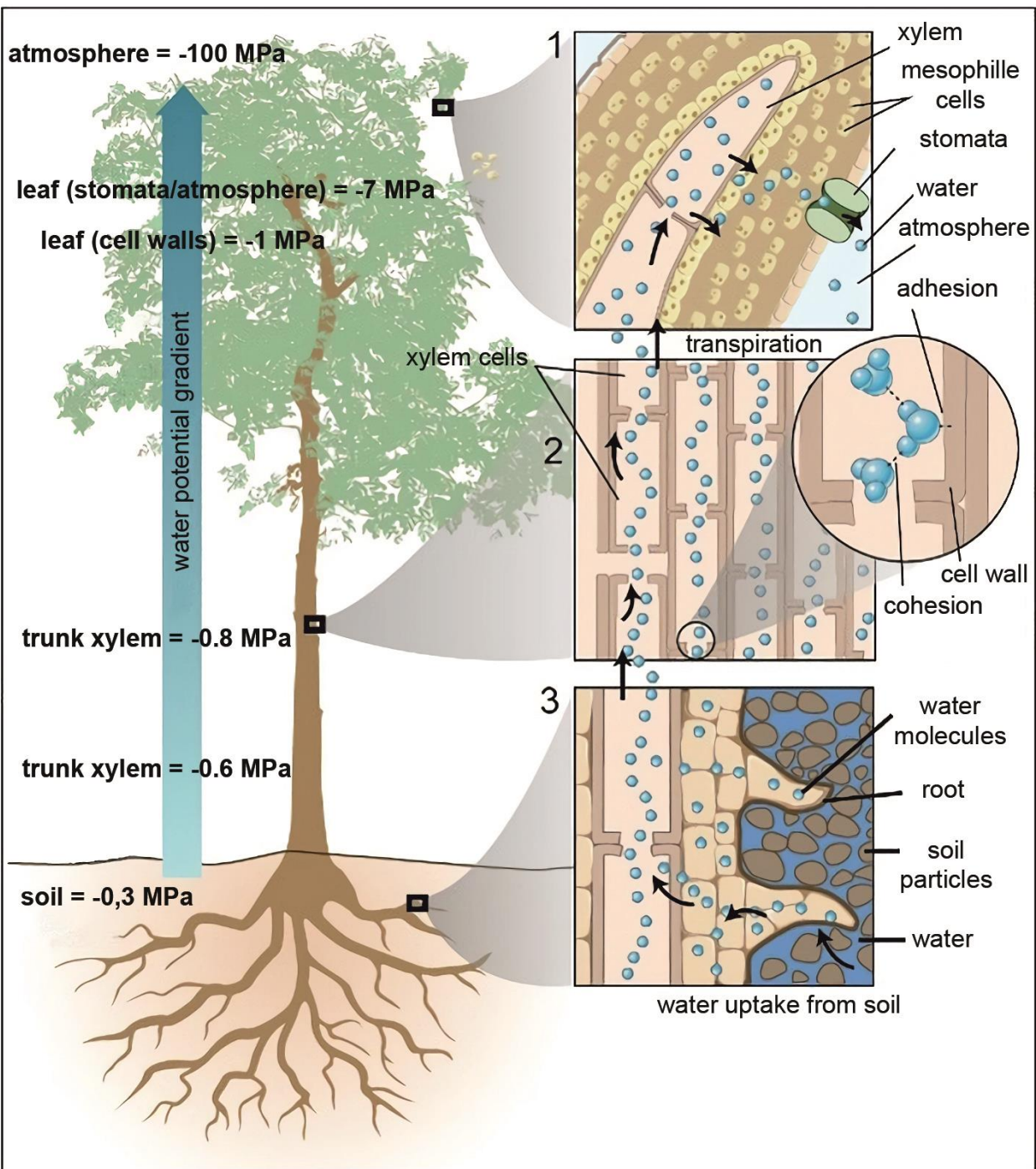
- The relative ease with which water moves through a part of the plant is expressed quantitatively using the following equation:

$$\text{water flow} = \Delta\psi / R$$

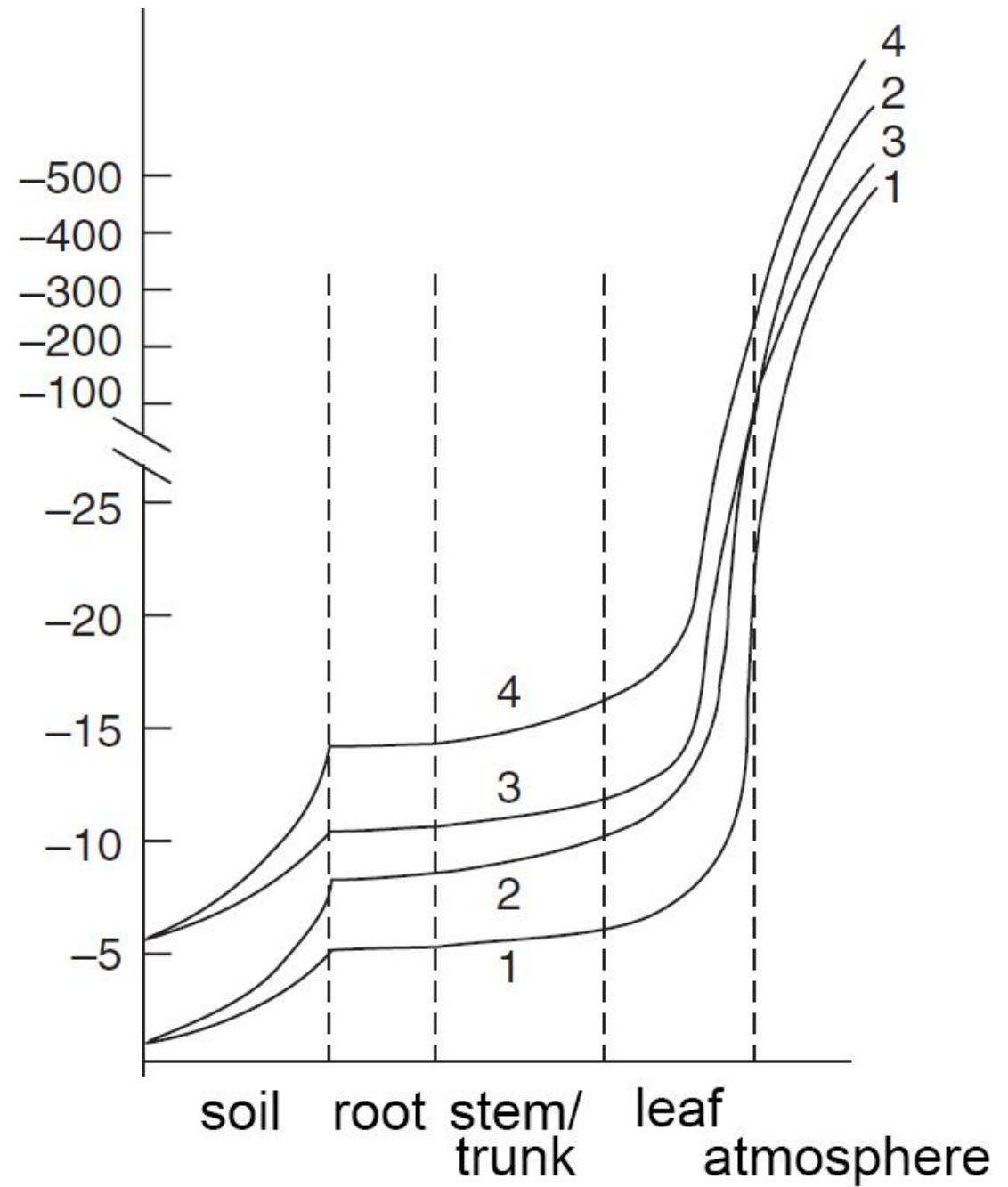
- which is analogous to **electron flow** (i) in an electrical circuit described by Ohm's law equation:

$$i = V / R$$

- where R is the **resistance** and V is the **voltage**. In the plant system, V is equivalent to the **water potential difference** driving flow ($\Delta\psi$) of water through/across a plant segment. Using these plant equivalents, the Ohm's law analogy can be used to quantify the hydraulic conductance (i.e., the inverse of hydraulic R) of individual segments (i.e., roots, stems, leaves) or the whole plant (from soil to atmosphere)



water potential (bar)



Water flow through the plants

- Unlike animals, plants lack a metabolically active pump like the heart to move fluid in their vascular system. Instead, water movement is passively driven by pressure and chemical potential gradients
- The bulk of water absorbed and transported through plants is moved by negative pressure generated by the evaporation of water from the leaves (i.e., transpiration); this process is commonly referred to as the **Cohesion-Tension (C-T) mechanism**
- This system is able to function because water is "cohesive" forces generated by hydrogen bonding. These hydrogen bonds allow water columns in the plant to sustain substantial tension (up to 30 MPa when water is contained in the minute capillaries found in plants) and helps explain how water can be transported to tree canopies 100 m above the soil surface

Evapotranspiration → calculating ET for turf grass (example)

$$ET = 0.622 \rho_a h_v \frac{(e_c - e_a)}{P}$$

bulk surface
resistance, r_s

movement within
canopy

stomata

soil / plant

e_c = canopy vapor pressure, kPa

e_a = partial pressure of water in atmosphere, kPa.

P = atmospheric pressure, kPa

h_v = water vapor transfer conductance, m s^{-1}

ρ_a = density of air, kg m^{-3}

0.622 = ratio of mass of water vapor to mass of dry air

$h_v = 1/(r_{av} + r_s)$, m s^{-1}

r_{av} = resistance to momentum transfer in atmosphere above canopy, s m^{-1}

r_s = bulk surface resistance, s m^{-1}

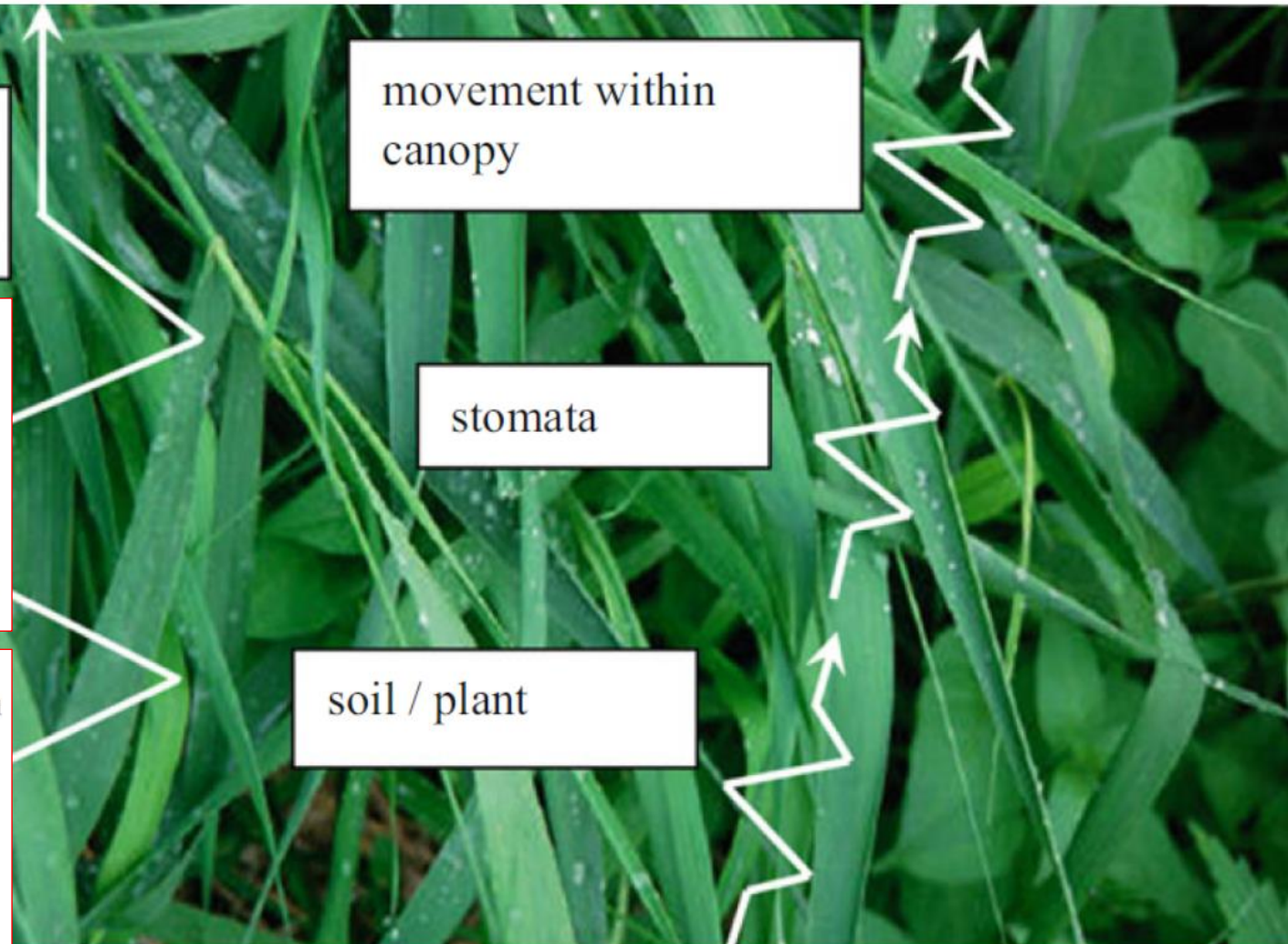
$\rho_a = \frac{e_a}{R_a T} + \frac{e_d}{R_d T} \sim 1.23 - 0.000112 * z$, kg m^{-3}

R_a = specific gas constant for water vapor, $0.4615 \text{ kJ kg}^{-1} \text{ K}^{-1}$

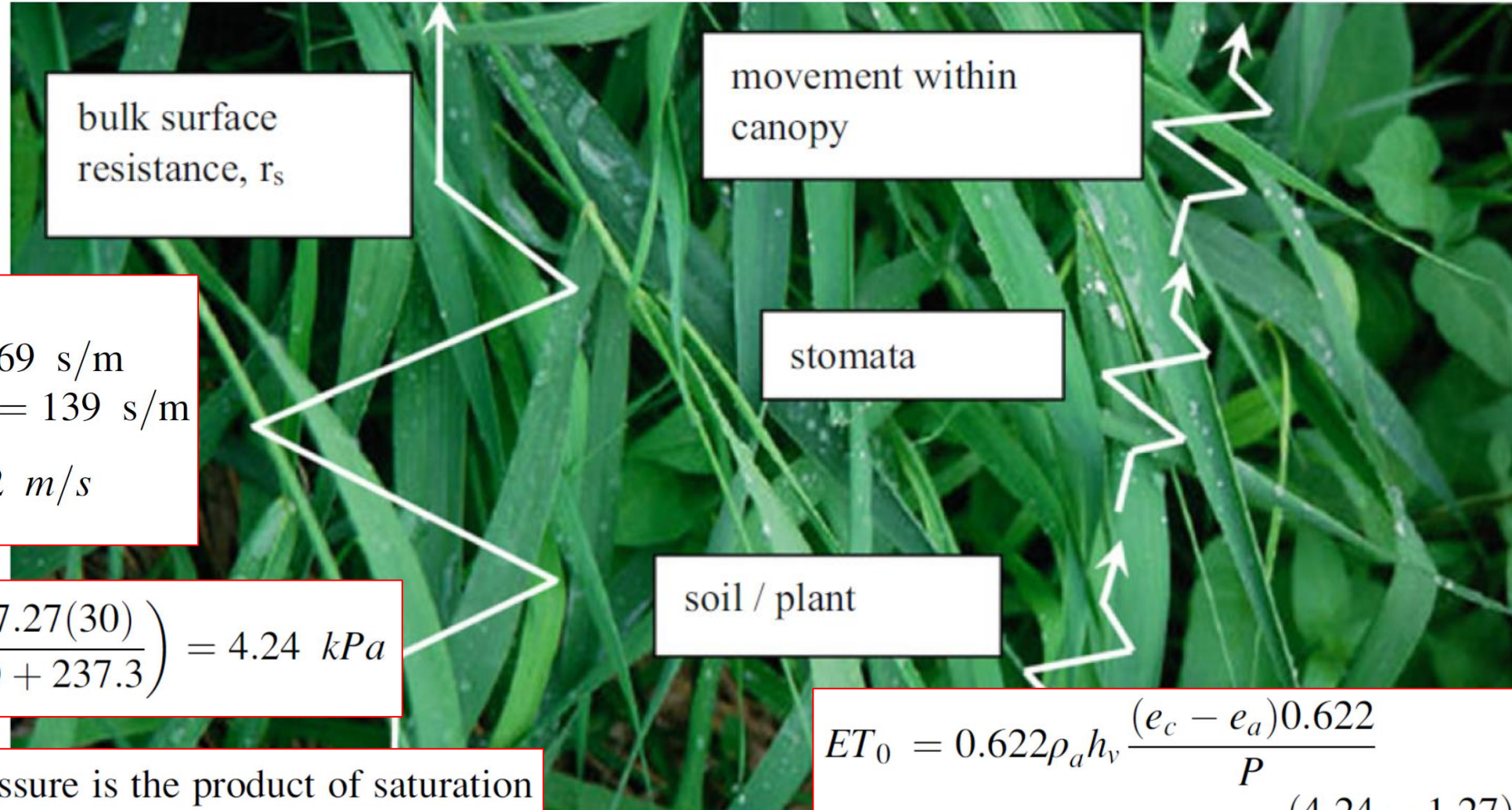
R_d = specific gas constant for dry air, $0.287 \text{ kJ kg}^{-1} \text{ K}^{-1}$

e_d = partial pressure of dry air, kPa

z = elevation above mean sea level, m.



Evapotranspiration → calculating ET for turf grass (example)



$$r_s = 70 \text{ s/m}$$

$$r_{av} = 208/U_2 = 208/3 = 69 \text{ s/m}$$

$$r_{total} = r_s + r_{av} = 70 + 69 = 139 \text{ s/m}$$

$$h_v = \frac{1}{r_{total}} = \frac{1}{139} = 0.0072 \text{ m/s}$$

$$e_c = e_s = 0.6108 \exp\left(\frac{17.27(30)}{30 + 237.3}\right) = 4.24 \text{ kPa}$$

The atmospheric vapor pressure is the product of saturation vapor pressure and relative humidity

$$e_a = e_s * (RH) / 100\% = 4.24 \text{ kPa} * 0.3 = 1.27 \text{ kPa}$$

$$ET_0 = 0.622 \rho_a h_v \frac{(e_c - e_a) 0.622}{P}$$

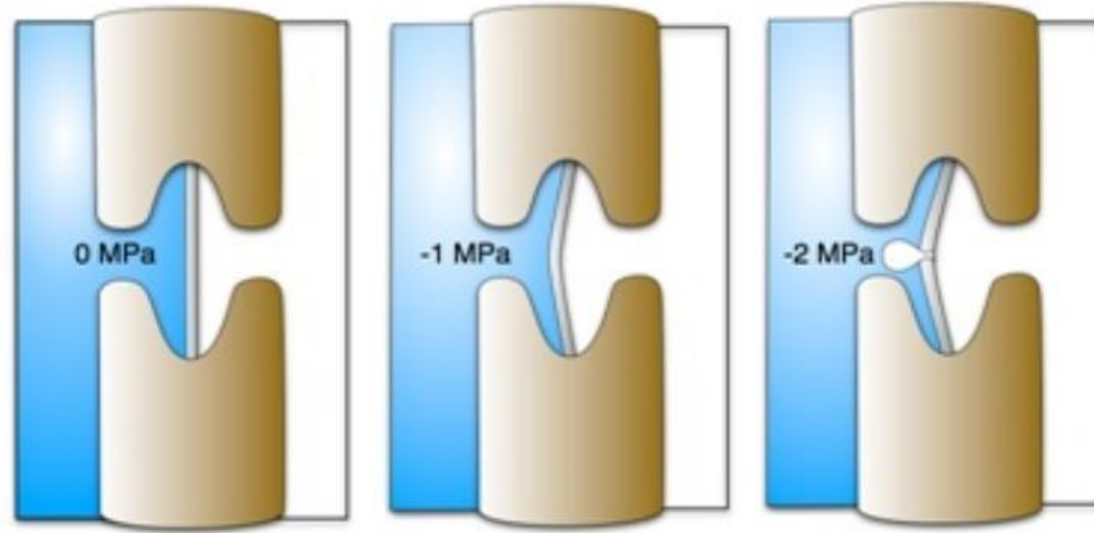
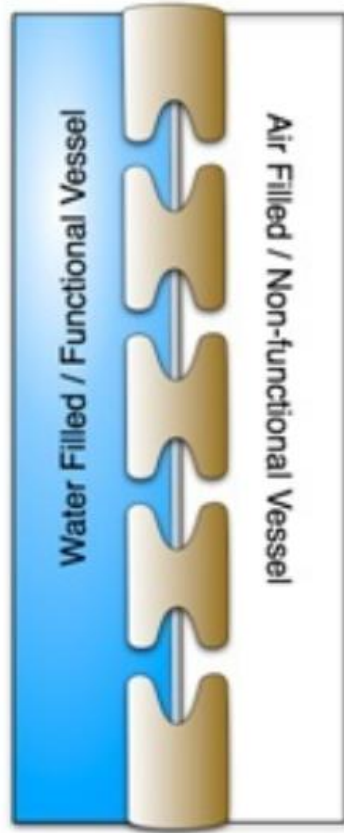
$$= 0.622 * 1.23 * 0.0072 \frac{(4.24 - 1.27)}{101.3}$$

$$= 0.00016 \text{ mm/s} = 0.58 \text{ mm/h}$$

Water flow through the plants (risk of embolism/cavitation)

- Water moving through plants is considered meta-stable because at a certain point the water column breaks when tension becomes excessive → cavitation
- After cavitation occurs, a gas bubble (i.e., embolism) can form and fill the conduit, effectively blocking water movement
- Both sub-zero temperatures and drought can cause embolisms. Freezing can induce embolism because air is forced out of solution when liquid water turns to ice. Drought induces embolism because as plants become drier tension in the water column increases
- There is a critical point where the tension exceeds the pressure required to pull air from an empty conduit to a filled conduit across a pit membrane — this is known as air seeding → breaks the water column

Water flow through the plants (risk of embolism/cavitation)



Water flow through the plants

- Apart from Cohesion-Tension (C-T) mechanism water moves in soil/plant also according to its chemical potential by **osmosis** — the diffusion of water
- Osmosis plays a central role in the movement of water between cells and various compartments within plants
- In the absence of transpiration, osmotic forces dominate the movement of water into roots.

$$\Psi_T = \Psi_m + \Psi_s + \Psi_p + \Psi_z$$

Osmotic component of water potential

Osmotic pressure in the diluted solution is proportional to concentration of osmotically active substance and temperature

$$\Pi = MRT \text{ (Pa)}$$

Π is osmotic pressure

M molar concentration

T temperature in Kelvins

R gas constant = 0.08205 L atm/mol K

water

solution

membrane with selective permeability

high difference in this case is proportional to concentration of osmotically active substances

