Ecophysiology

Please Note: Some of the slides are Animated and are best viewed as a Slide Show; some slides have attached notes below the slides and these are best viewed in Normal (editing) view.

4. Water & Plants

Rainfall Stimulates Plant Growth

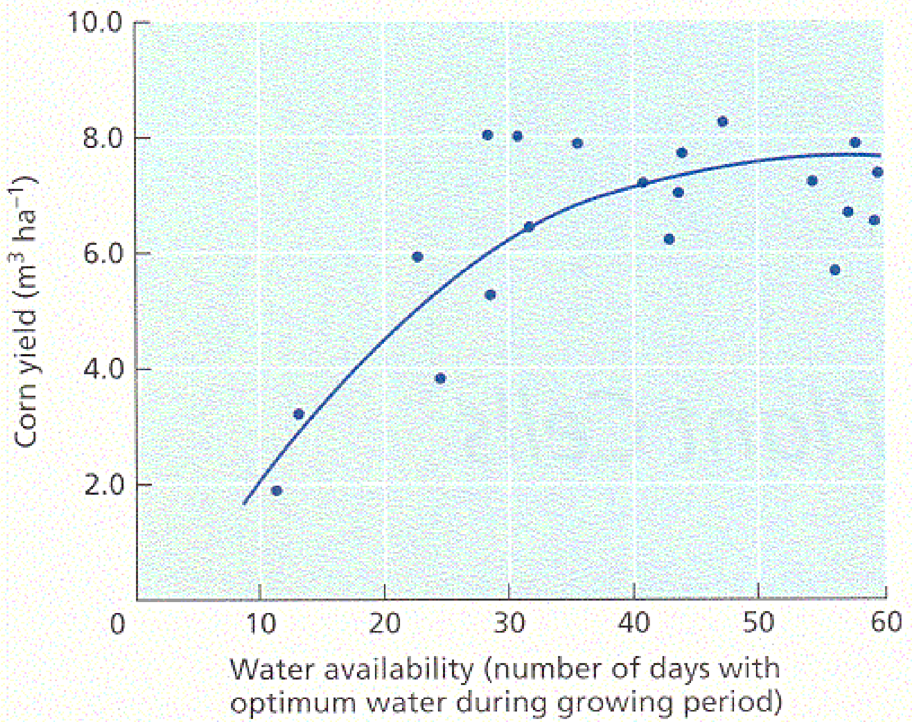


FIGURE 3.1 Corn yield as a function of water availability. The data plotted here were gathered at an Iowa farm over a 4-year period. Water availability was assessed as the number of days without water stress during a 9-week growing period. (Data from *Weather and Our Food Supply* 1964.)

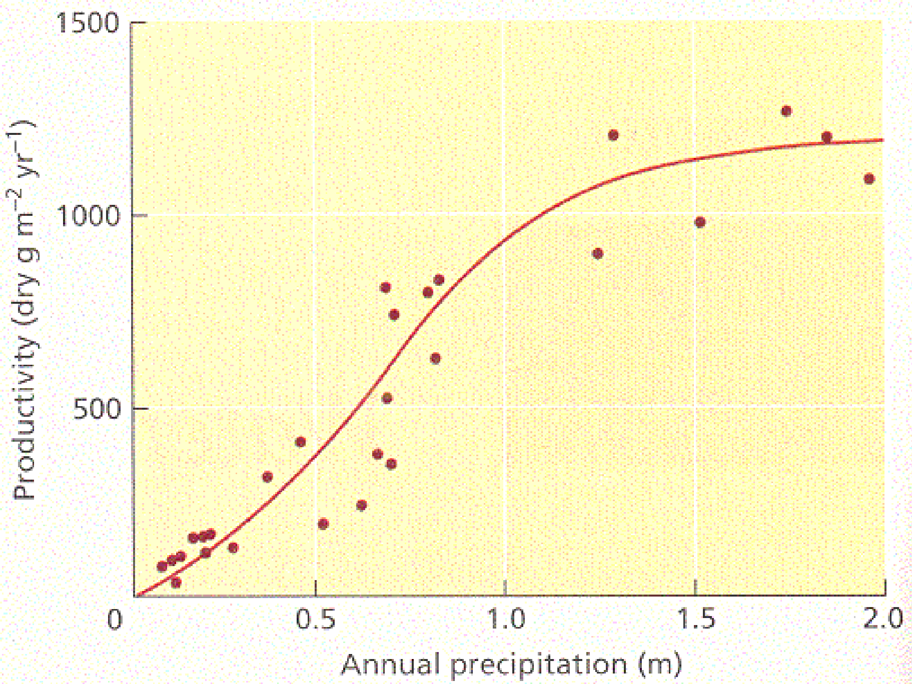


FIGURE 3.2 Productivity of various ecosystems as a function of annual precipitation. Productivity was estimated as net aboveground accumulation of organic matter through growth and reproduction. (After Whittaker 1970.)

Water Relations:
Water Potential, Y_{H_2O}

Studying Water Relations in Plants involves:

– Assessing the *Amount* of Water in Different Locations (Soil, Xylem, Cytoplasm, etc.)

– Assessing the *Driving Force* for Water Flow between Locations (Differences in Amounts, Gravity, Pressure)

– Assessing the *Conduction* (Resistance) of Flow Pathway

Flow (Flux) = Driving Force x Conductance

= Driving Force / Resistance

Water Potential, Y_{H_2O}

What Forces Make H_2O Move?

Differences in:

Concentration	(**Molar**, Kg/m^{-3}, ..)
Pressure	(**Pa**, Bar, N m^{-2}<..)
Height (gravity)	(**m**,..)

? To Determine Force for H_2O Movement Between 2 Locations, Forces have to be Summed in Each and Difference Taken.

Total Force = (Force in Location A) – (Force in Location B)

Water Potential, Y_{H_2O}

How can the Amount of H_20 be As

Concentration?

1000g / 18g = 55.5 M or 1000 K

Pressure?

P=(n/V)RT (n/V = mol/Litre; T

in ° K; R, Gas Constant =

8.314 L-KPa K^{-1} mol^{-1},

or 0.008314 L-MPa K^{-1} mol^{-1}

Values of R	Units ($V \cdot P \cdot T^{-1} \cdot n^{-1}$)
8.314472	$J \cdot K^{-1} \cdot mol^{-1}$
0.0820574587	$L \cdot atm \cdot K^{-1} \cdot mol^{-1}$
83.14472	$cm^3 \cdot bar \cdot mol^{-1} \cdot K^{-1}$
8.20574587 × 10^{-5}	$m^3 \cdot atm \cdot K^{-1} \cdot mol^{-1}$
8.314472	$cm^3 \cdot MPa \cdot K^{-1} \cdot mol^{-1}$
8.314472	$L \cdot kPa \cdot K^{-1} \cdot mol^{-1}$
8.314472	$m^3 \cdot Pa \cdot K^{-1} \cdot mol^{-1}$
62.36367	$L \cdot mmHg \cdot K^{-1} \cdot mol^{-1}$
62.36367	$L \cdot Torr \cdot K^{-1} \cdot mol^{-1}$
83.14472	$L \cdot mbar \cdot K^{-1} \cdot mol^{-1}$
0.08314472	$L \cdot bar \cdot K^{-1} \cdot mol^{-1}$
1.987	$cal \cdot K^{-1} \cdot mol^{-1}$
6.132440	$lbf \cdot ft \cdot K^{-1} \cdot g\text{-}mol^{-1}$
10.73159	$ft^3 \cdot psi \cdot °R^{-1} \cdot lb\text{-}mol^{-1}$
0.7302413	$ft^3 \cdot atm \cdot °R^{-1} \cdot lb\text{-}mol^{-1}$
998.9701	$ft^3 \cdot mmHg \cdot K^{-1} \cdot lb\text{-}mol^{-1}$
8.314472 × 10^7	$erg \cdot K^{-1} \cdot mol^{-1}$

For

Pure H_2O, n/V = 0 so Y_{H_2O} = 0 x 0.0083 x 298 = 0 MPa

1 M Glucose n/V = 1, Y_{H_2O} = 1 x 0.0083 x 298 = -2.45 MPa

1M NaCl, n/V =2, Y_{H_2O} = -4.90 MPa

Water Potential, Ψ_{H_2O}

The ‘Amount’ Force is Termed

Solute Potential Ψs

or

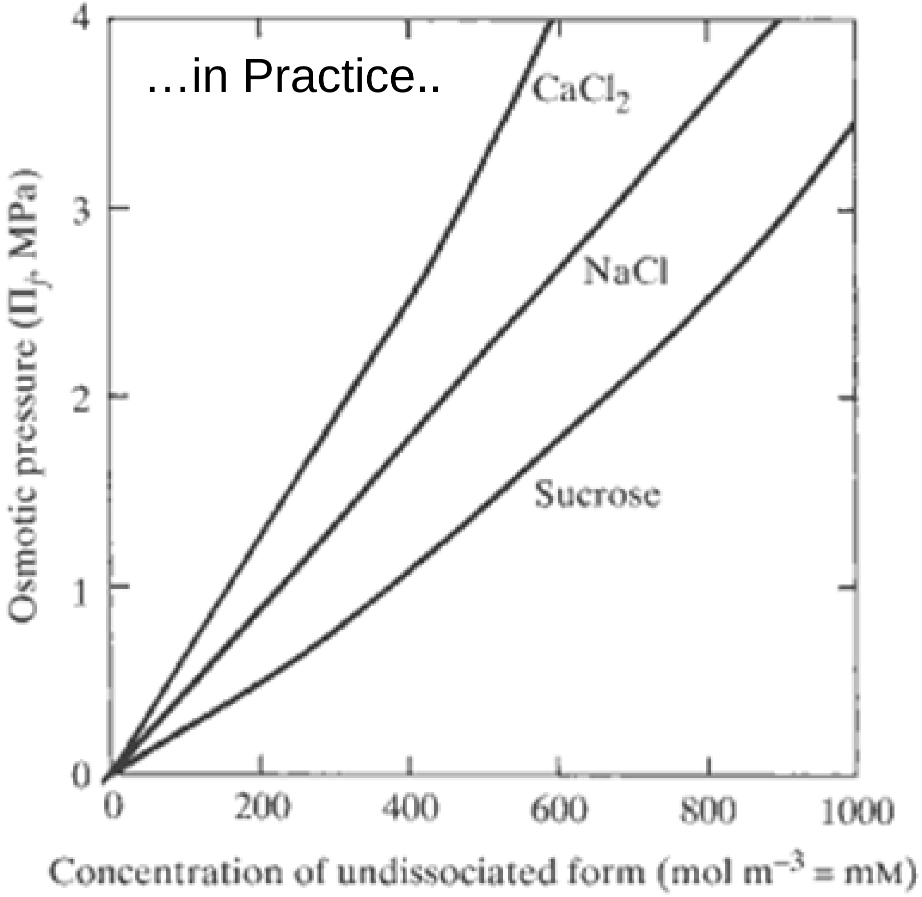
Osmotic Potential $+\pi$

or Osmotic Pressure $-\pi$

This Force is Dependent o
Particles in Solution (a C

Vant Hoff $P=(n/V)RT$ (

- 1 M Glucose n/V = 1, Ψ_{H_2O} = 1 x 0.0083 x 2
- 1M NaCl, n/V =2, Ψ_{H_2O}



Water Potential, Y_{H_2O}

The Pressure Term is Expressed in

Pascals (Pa) = Force / Area

= Newtons / Area

(1 N = 1Kg m s^{-2})

Water Potential, Y$_{H_2O}$

How can the Gravitational Force on H_20 be Assessed?

Force = $r_w gh$ r_w, density = 1000Kg m^{-3}

g, Gravitational Constant = 9.806 m s^{-2}

h, Difference in height between Locations (m)

So, 10m height difference = 98,060 Kg m^{-1} s^{-2}

Expressed on a m^{-2} basis ⇨ Force . m^{-2} = 98,060 Kg m^2 s^{-2}

Pressure (Pa) = 98,060 N m^{-2}

or ~0.1 MPa

Water Potential, Y_{H_2O}

The Total Force is Sum of Forces for All Terms

= Amount + Pressure + Gravity

And Called the ‘Chemical Potential of Water’

Or the Water Potential, Y_{H_2O}

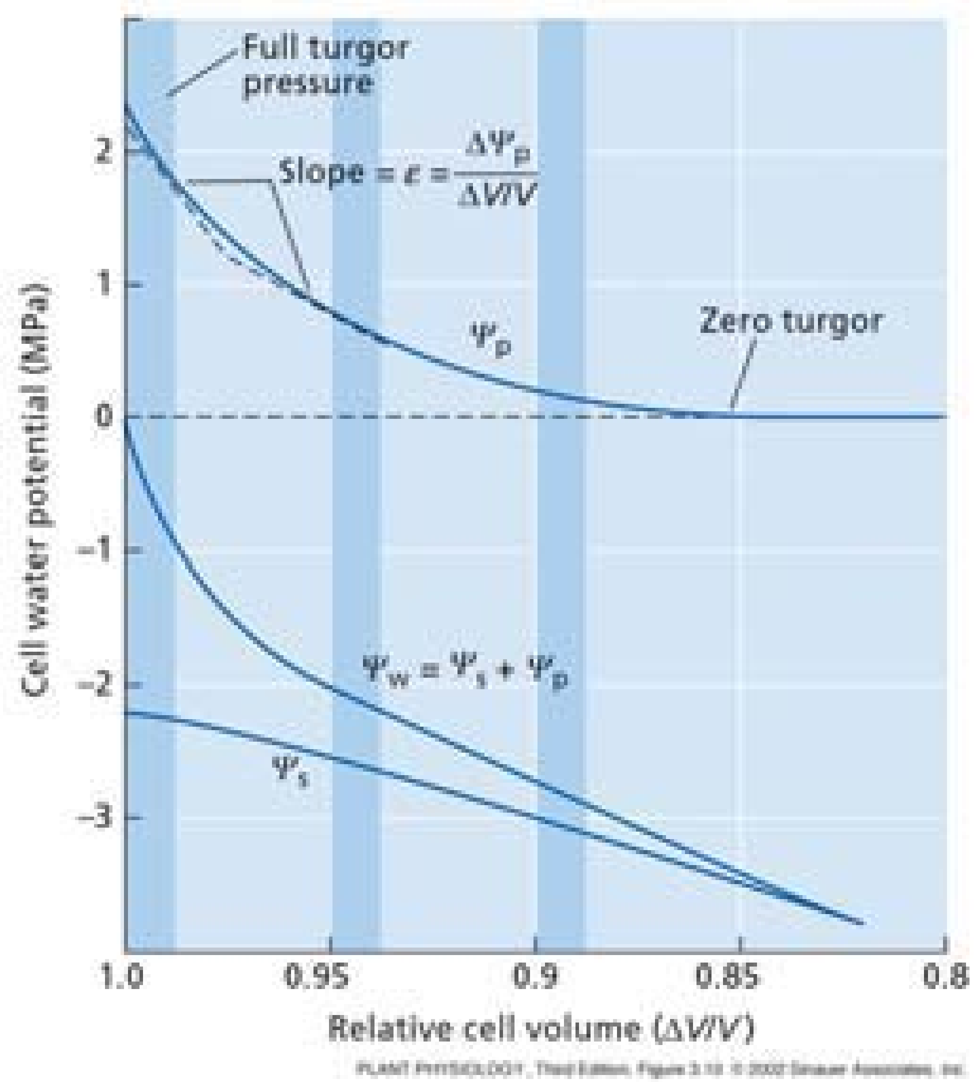
$Y_{H_2O} = Y_s + Y_P + Y_g$, often the Y_g term can is small

$Y_{H_2O} = Y_s + Y_P$ or

$Y_{H_2O} = p + P$

Hofler Diagrams

Hofler Diagrams are a useful way of viewing the water relations of plant cells.



Water Potential, Y$_{H_2O}$

Be careful!

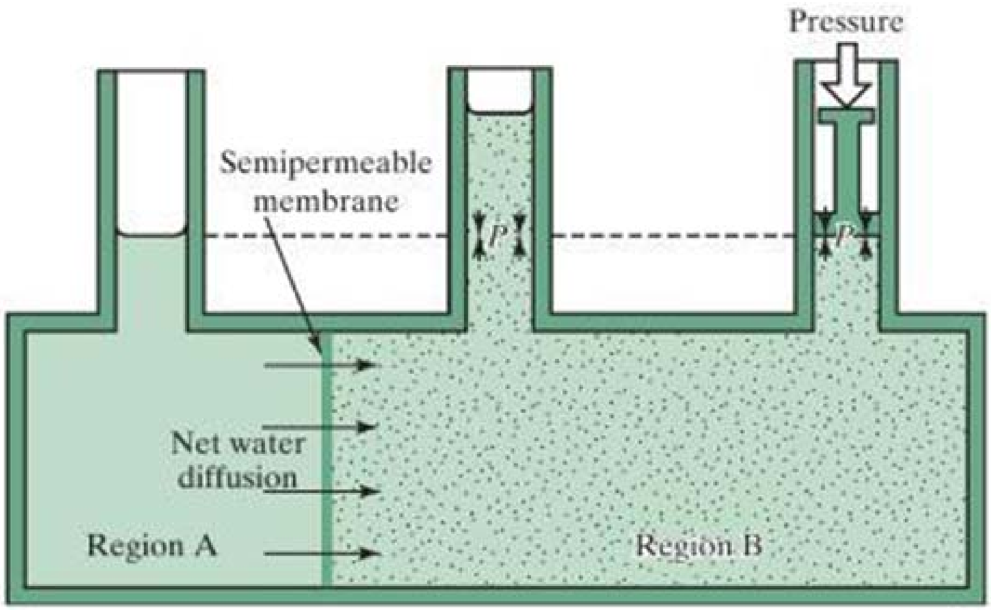
Solute Potential Ys

Osmotic Potential +p

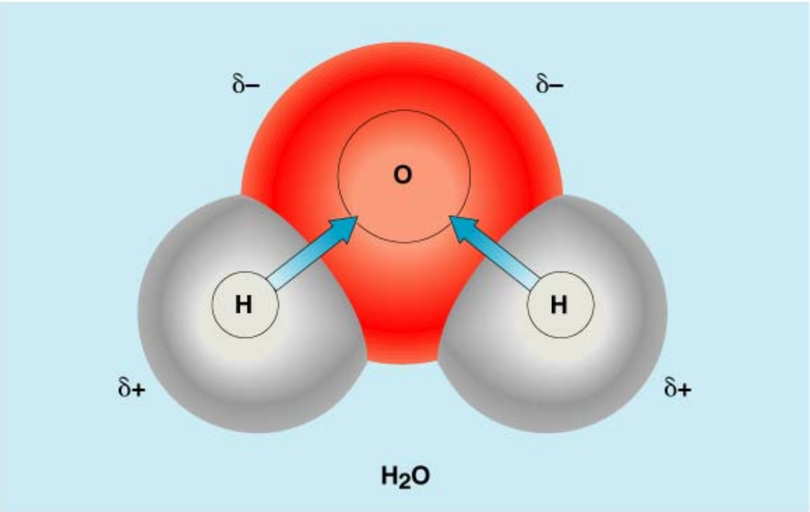
Osmotic Pressure –p

Solution of 1M sucrose has the following values:

Ys	= -2.4MPa
p	= -2.4 MPa
–p	= +2.4 MPa



Water Has Special Properties



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Water Can 'Hydrogen Bond'

- With Other Water Molecules
- With Other Small Molecules
- With Surfaces

Hydrogen bonding between H_2O

⇨ High Specific Heat (75.6 J mol^{-1} ° K^{-1})

⇨ High Latent Heat of Vaporization (44 KJ mol^{-1})

⇨ Surface Tension / Tensile Strength

Hydrogen Bonding Small Molecules

⇨Water is an Excellent Solvent for Polar Compounds

Hydrogen Bonding With Surfaces

⇨ Capillary Action

Water Movement

Water Can Move Between Two Locations If There Is:

Concentration Gradient (By Diffusion)

J_{H_2O} = -D_{H_2O} (DC_{H_2O}/Dx) - Fick's Law

(J_{H_2O}, water Flux; D_{H_2O}, Diffusion Coefficient – 2.272 10^{-9} m^2 s^{-1}; C_{H_2O}, Concentration; x, distance between locations)

Pressure Gradient (By Pressure-driven Flow)

Poiseuille's Equation..

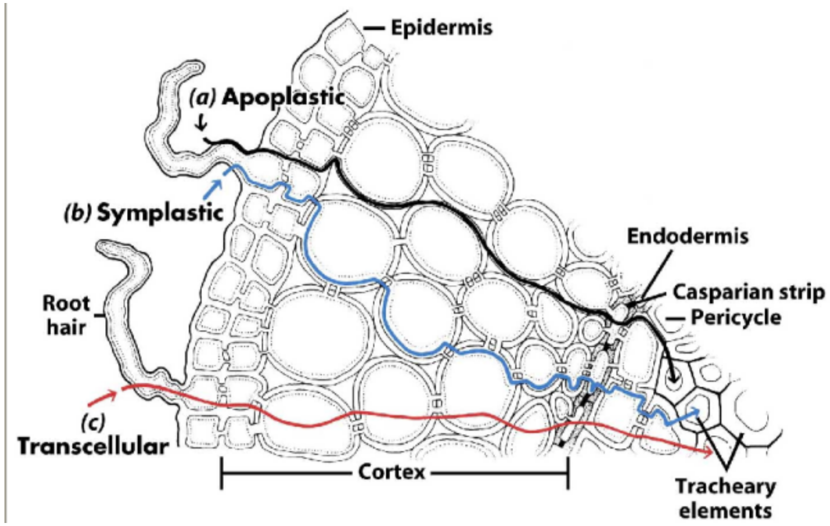
$$J_{H_2O} = \left(\frac{\pi r^4}{8\eta}\right)\left(\frac{\Delta\psi_p}{\Delta x}\right) \qquad J_{H_2O} = \left(\Delta\psi_p \Big/ 8\eta\left[\frac{\Delta x}{\pi r^4}\right] \right)$$

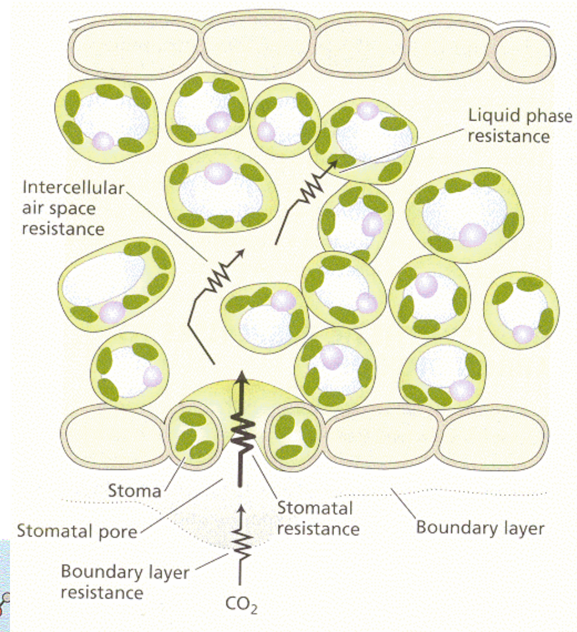
Height Gradient (By Gravitational 'Pull')

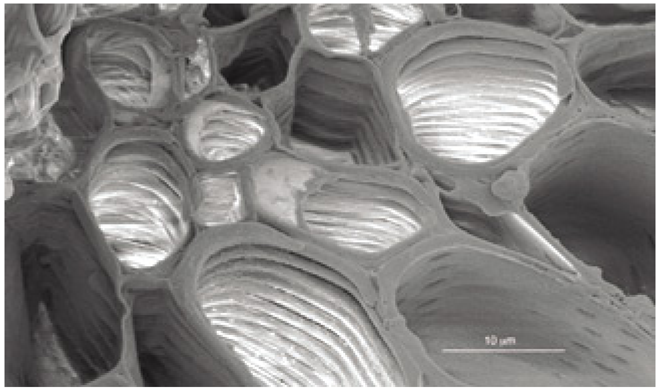
J_{H_2O} = $r_w$gh

Hydraulic Conductivity

A Water Potential Gradient (DY$_{H_20}$)Will Not Necessarily Result in Water Flow – a Conduction Pathway is Required (Resistance)

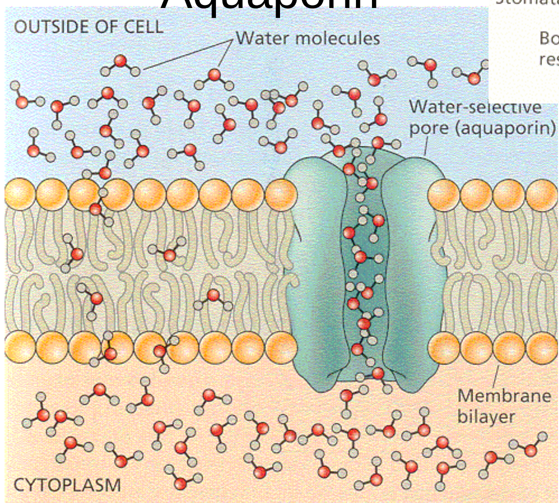




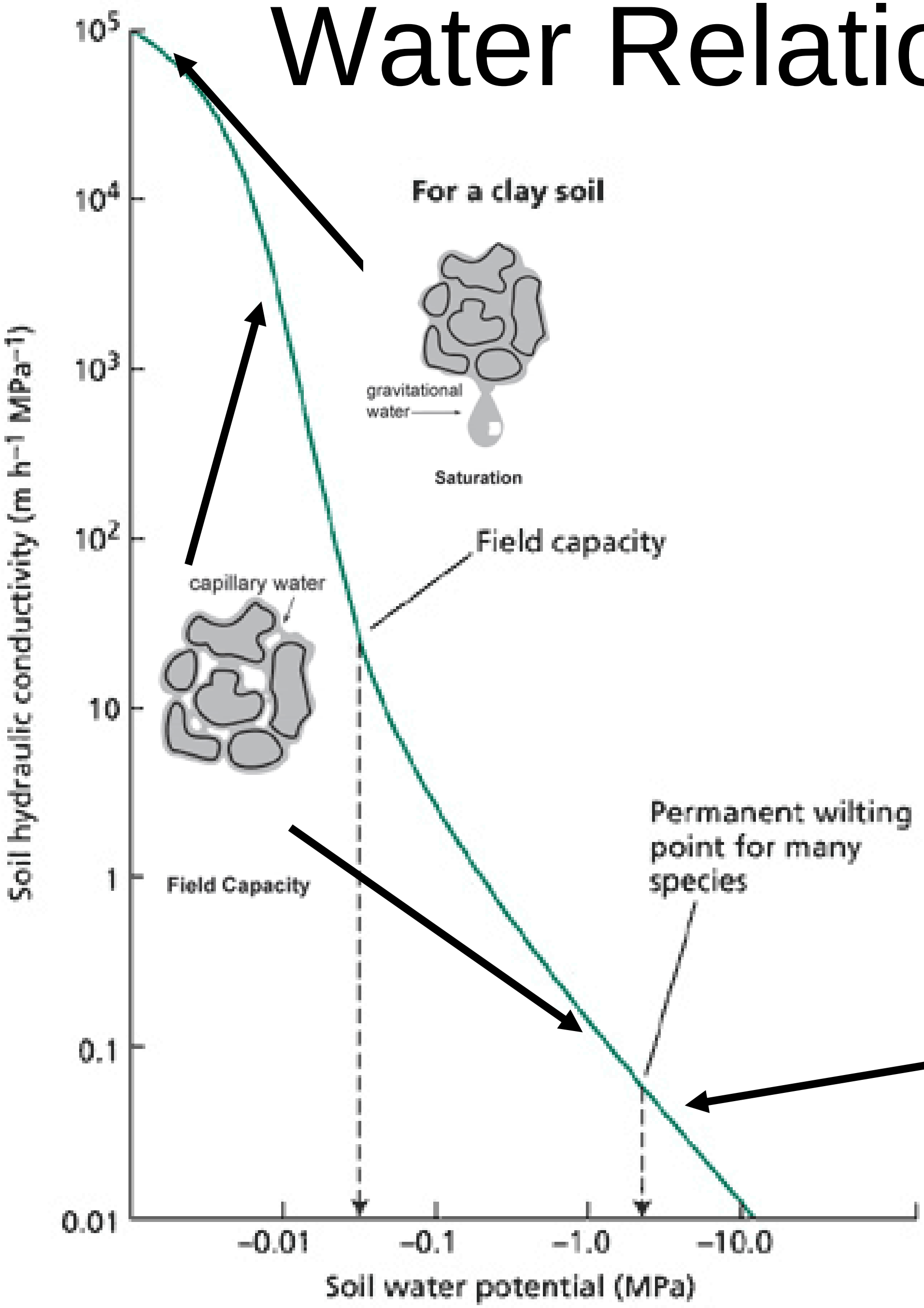


Xylem Vessels in Arabisopsis

Aquaporin

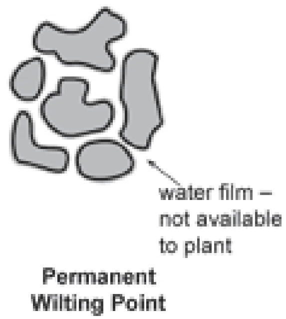


Water Relations in the Soil



Field Capacity is the amount of water the soil can hold after excess drainage

Permanent Wilting Point varies for different plants – Y_W beyond which turgor can not be regained,



Typical Pore-Size & Soil Water Contents of Different Soils

	Soil Type		
Parameter	Sand	Loam	Clay
Pore Space (% of Total)			
> 30 mm particles	75	18	6
0.2-30 mm	22	48	40
< 0.2 mm	3	34	53
Water Content (% of Volume)			
Field Capacity	10	20	40
Permanent Wilting Point	5	10	20

The Matric Potential, Y_{H_2O}

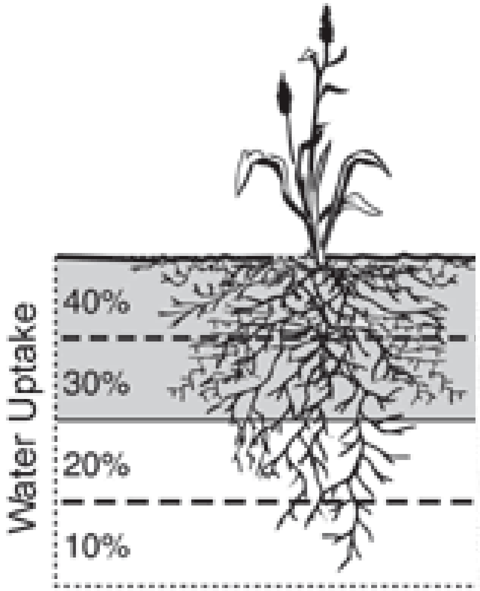
As Y_{H_2O} Falls a 'New' Force Increases,

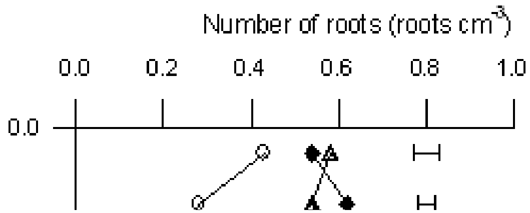
Y_m, the Matric Potential

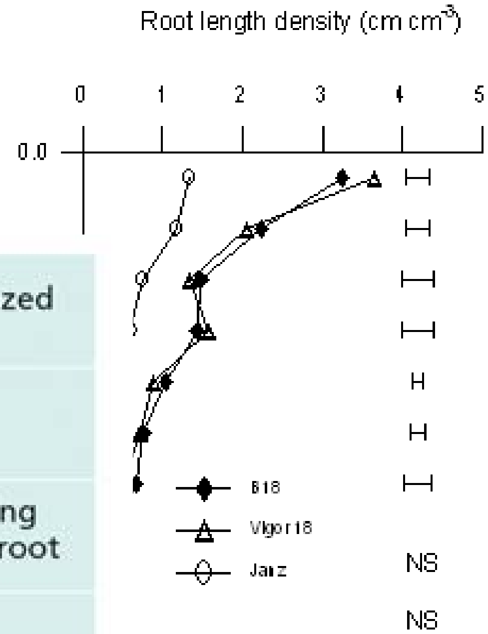
$$Y_{H_2O} = Y_s + Y_P + Y_m$$

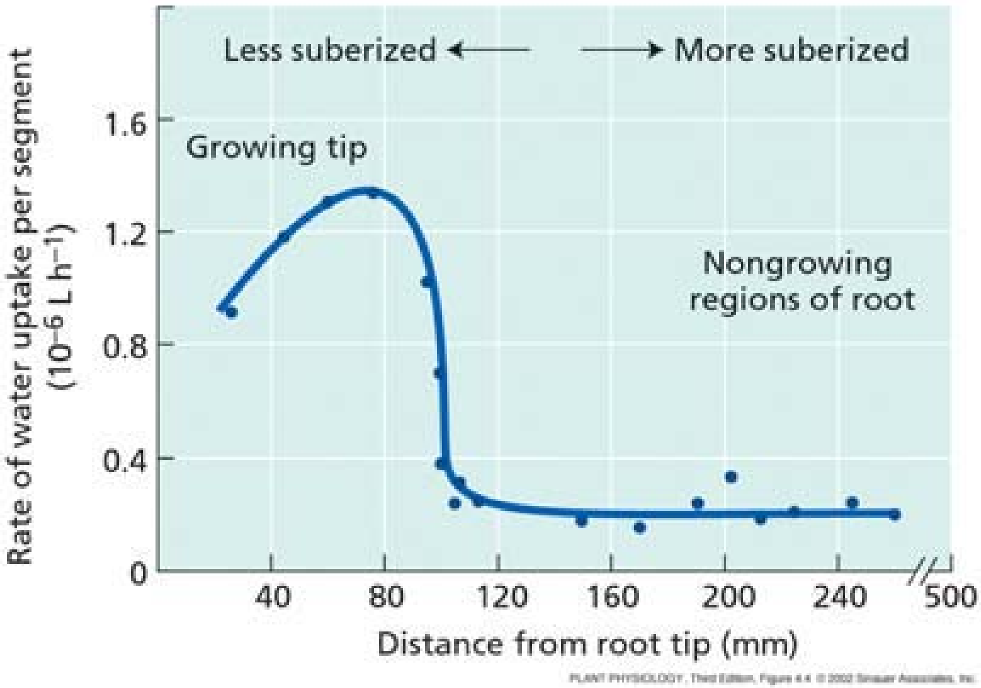
Y_m arises when the film of water on soil particles are only a few layers thick. The fixed electrical charges on the soil particles form strong H-bonds with the water's dipoles binding the water tightly. The Y_m term is used for convenience. In fact it is not a 'New' Force, but appears to be so. Y_m can be accounted for by the Y_s and Y_P terms, but not easily – for this reason it is considered as a separate term.

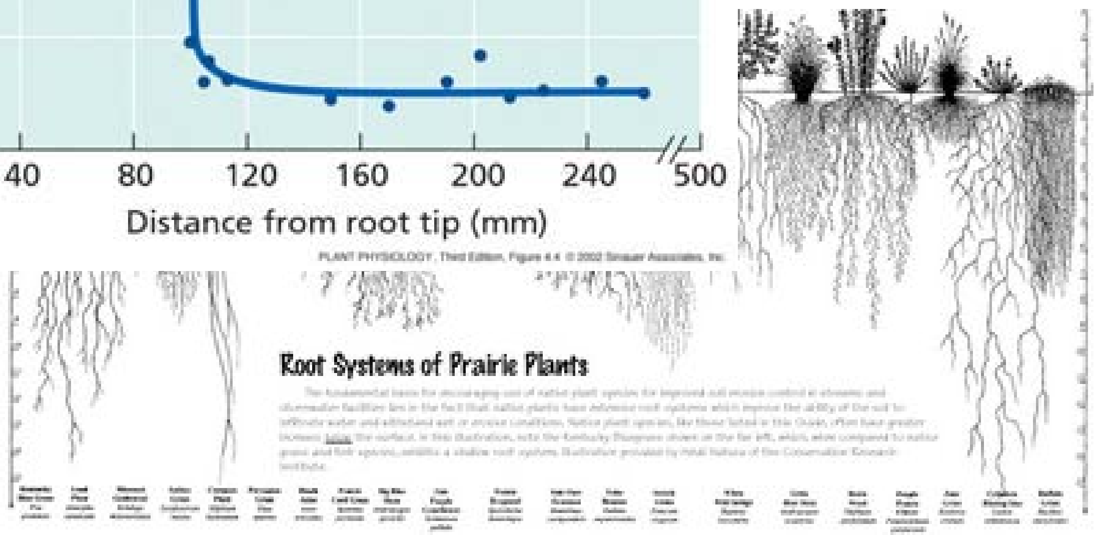
Water Extraction From the Soil











Root Structure is Geneti Determined but

Roots also sense and grow towards moisture.

Root Statistics…

- A single grass plant in 1 litre of soil:
- Length of roots = 12 km
- Surface area = 5 m^{-2}
- Length of roots + root hairs = 220 km
- Surface area = 14 m^{-2}
- Degree of soil contact = 1%
- Maximum distance for $H_2O$to
  move to a root = 10 mm

Root Morphology Affects Water Uptake

Taproots can extract water from deep water tables

Cowpea or

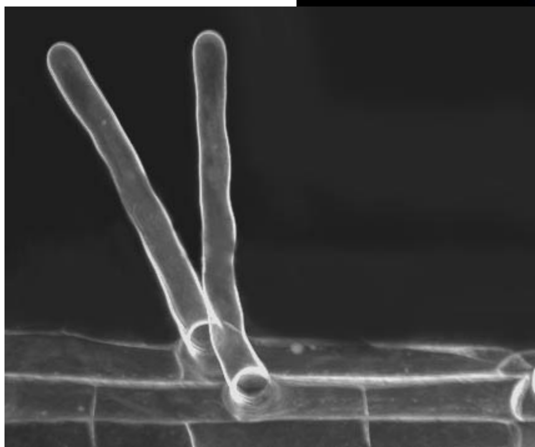
Blackeye Bean

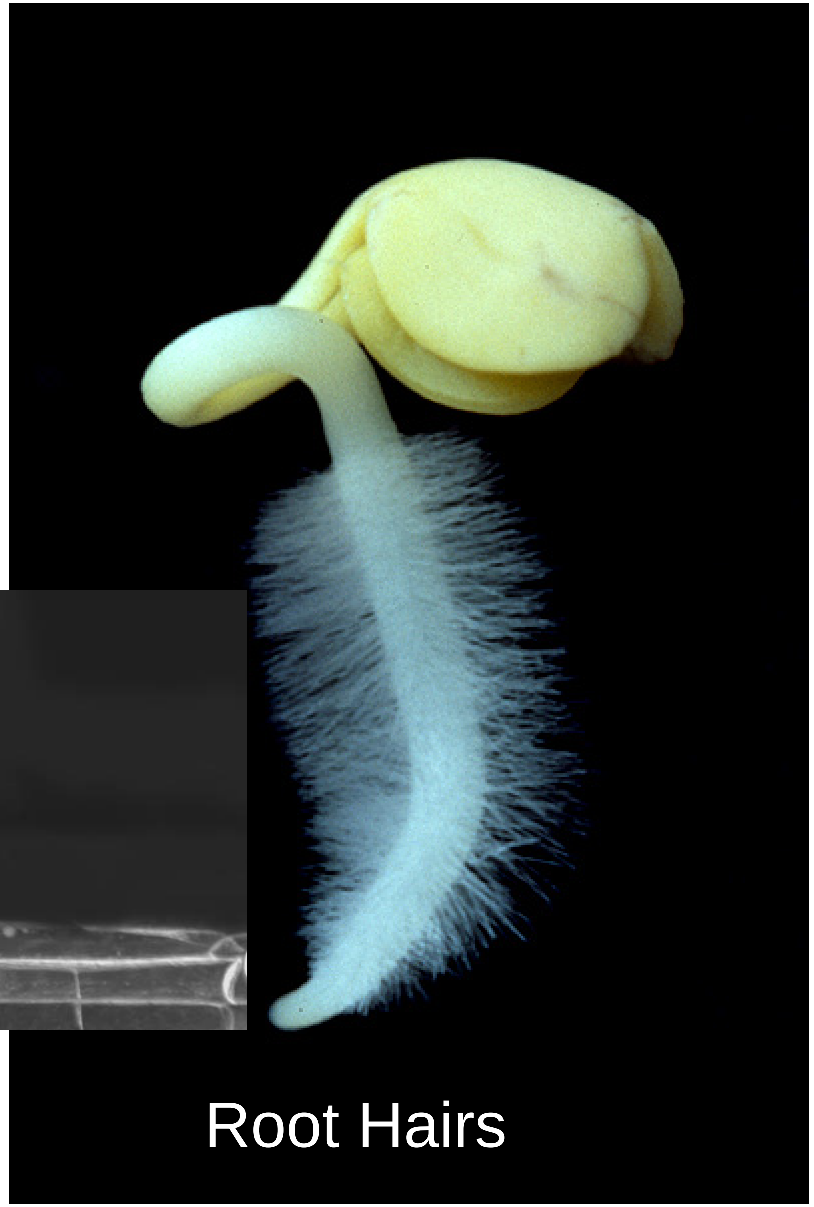
(*Vigna unguliculata*)

…but the Major Crops Don't Do This…

Extensive root hair systems greatly increases the absorptive properties of roots –

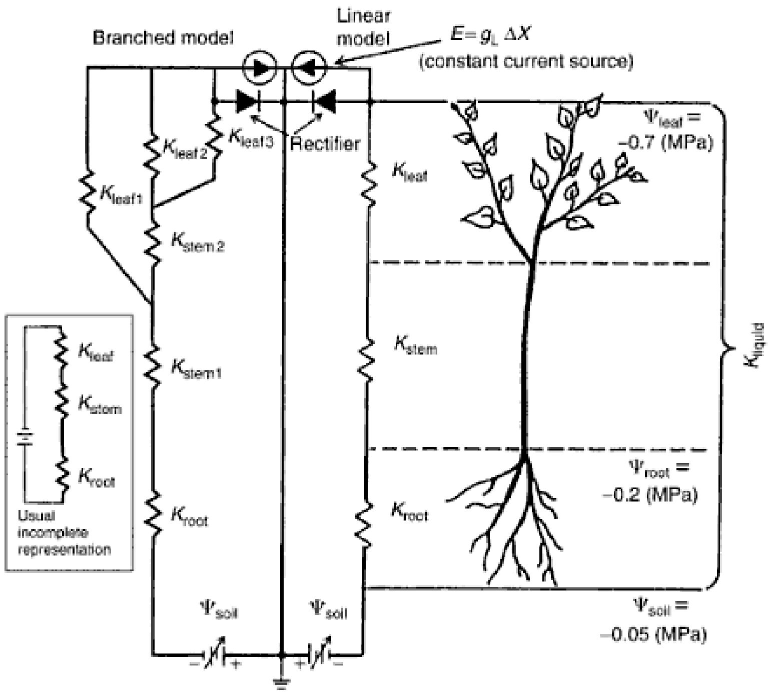
Some plants produce root hairs when drought stressed

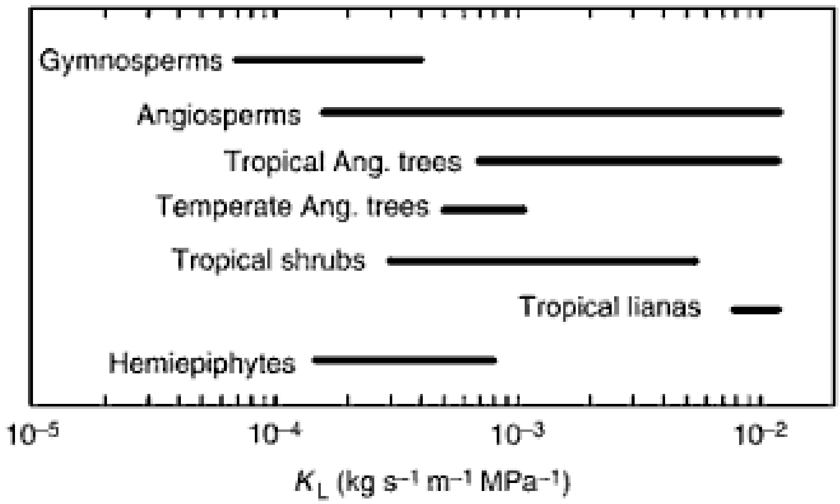


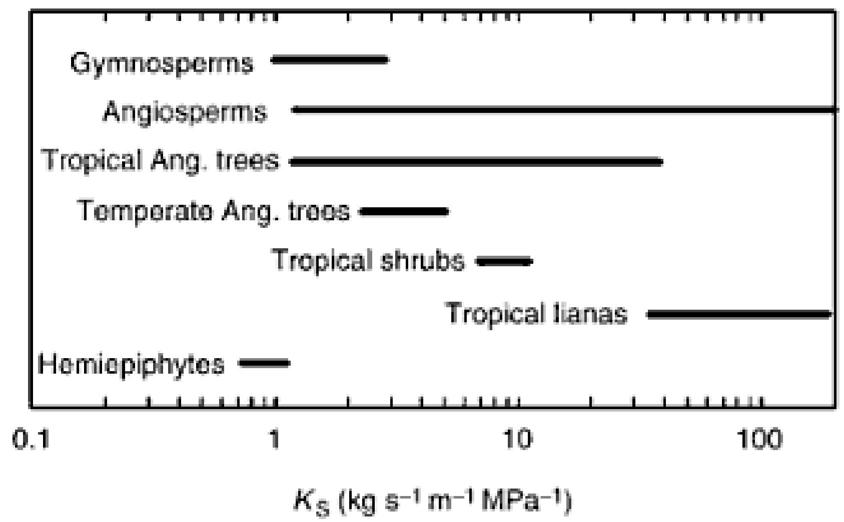


What determines root development?

Hydraulic Conductivity In The Xylem Varies Between Species







K_L = Leaf Specific Conductivity

K_S = Specific Hydraulic Conductivity

Capillary Action

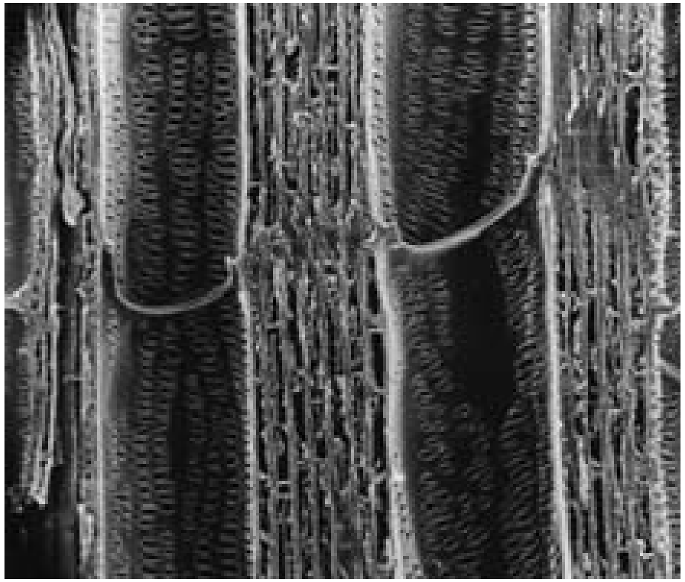
- To calculate the height liquid can be raised by capillarity:
- $h = 2T\cos ø \div dgr$
- h = height of capillary (meters)
- T = surface tension (@20C,
- T for water = $0.0728 Nm^{-1}$)
- cos ø = lifting component of meniscus angle
  (approx = 1)
- d = density of liquid ($998 kgm^{-3}$)
- g = gravitational constant ($9.80\ ms^{-2}$)
- r = radius of capillary (in meters)

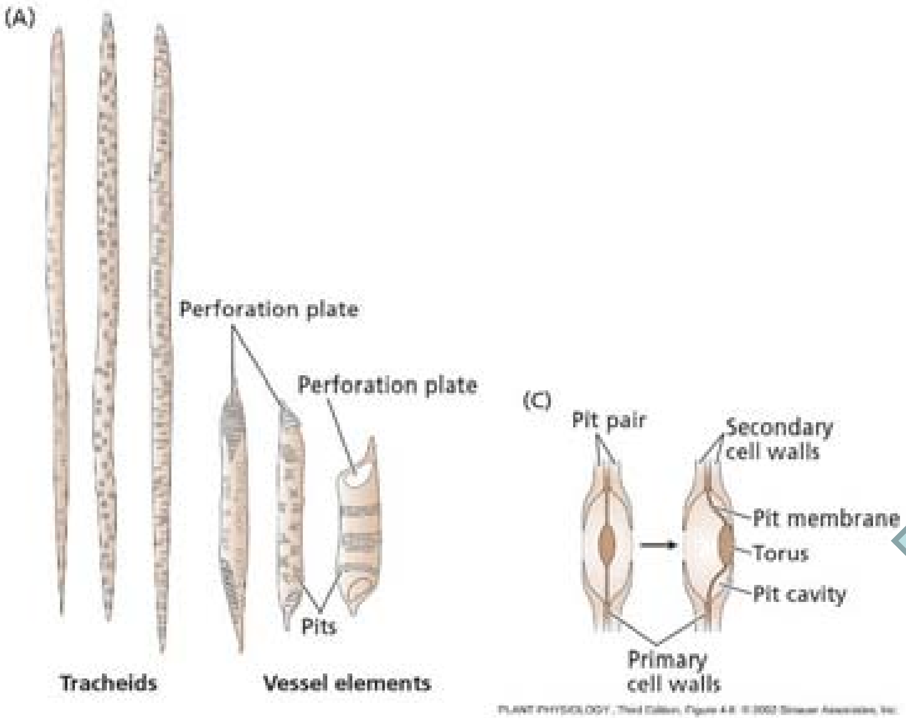
Capillary Action

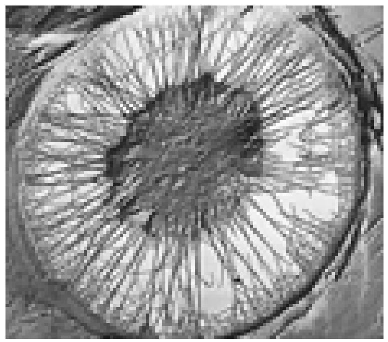
Capillary diam (μ m)	height of water column (m)
0.005	3000
1	15.3
10	1.53
40	0.38

Point: Height to which a column of water can be lifted by a capillary is inversely related to the diameter of the capillary.

Xylem Vessels: Ultrastructure





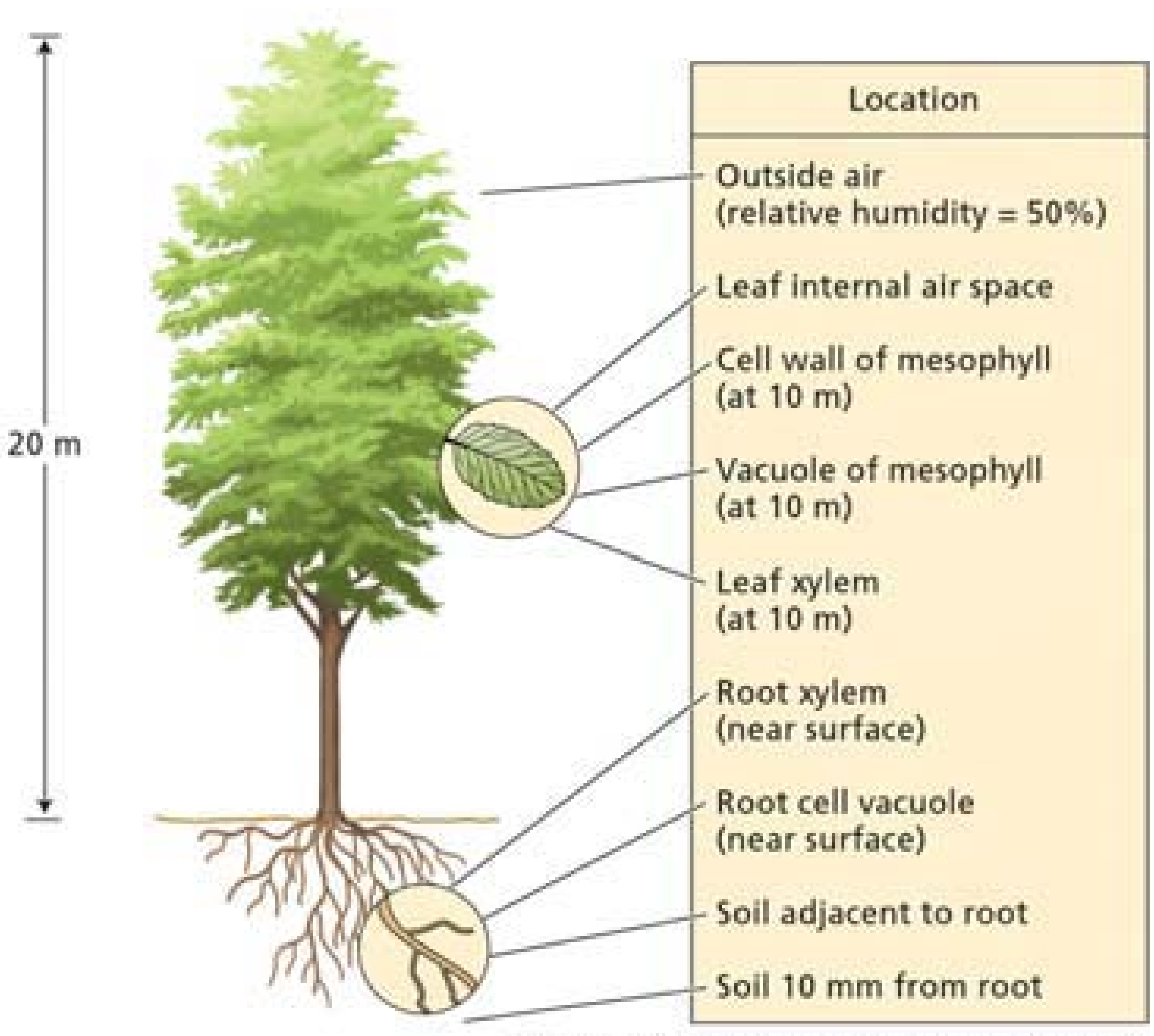


Pressure Required to Move Water Up a Tree

Pressure gradient = 0.02 MPa m^{-1}

- Tree height = 100 meters (a Redwood tree)
- Total Pressure Needed = 2.0 MPa
- Weight of Water … added Force to overcome
  - 100 meters X 0.01MPa m^{-1} = 1MPa
- Total Pressure Needed = <u>3MPa</u>

The Soil-Plant-Air Continuum



The presence of a continuous liquid water continuum from the soil to the atmosphere is required for transpiration.

Typical YH_2O Values in S-P-A Continuum

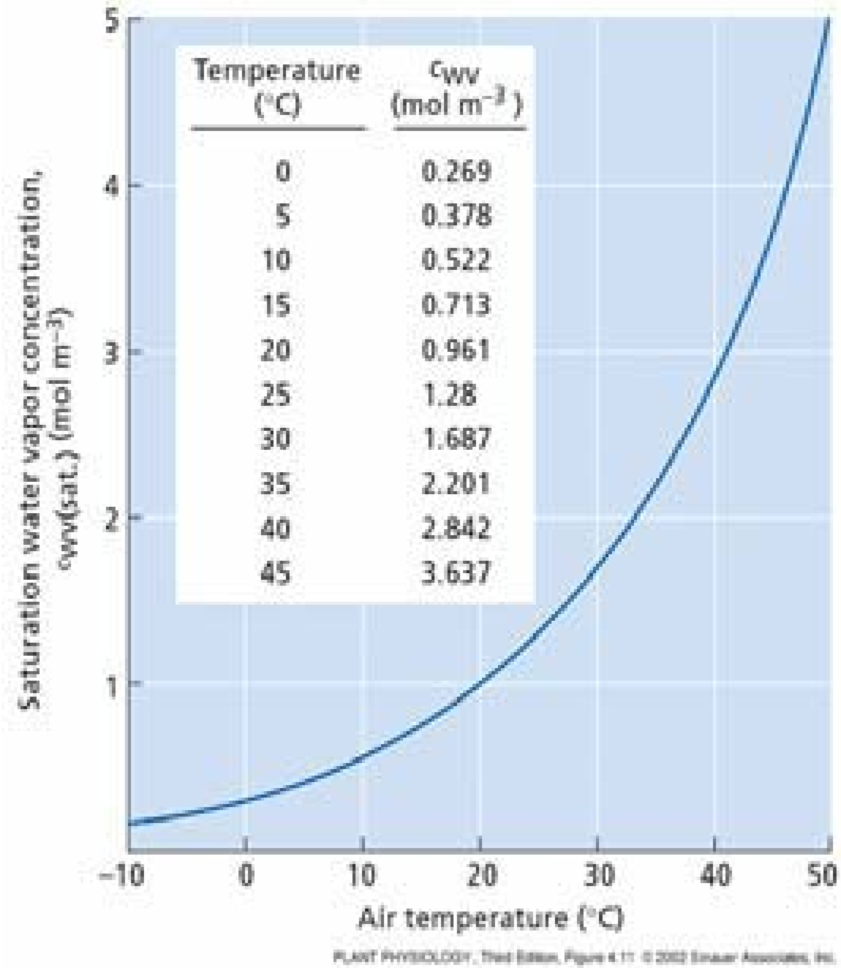
Typical y_{H2O} Values Along a Transpiration Path:

Note the very low value in air.

Note: It is the Water Vapour Presuure Deficit (VPD) that Determines Transpiration Rates (see explanation in notes below).

Location	Water potential and its components (in MPa)				
	Water potential (Ψ_w)	Pressure (Ψ_p)	Osmotic potential (Ψ_s)	Gravity (Ψ_g)	Water potential in gas phase ($\frac{RT}{\bar{V}_w}\ln[RH]$)
Outside air (relative humidity = 50%)	–95.2				–95.2
Leaf internal air space	–0.8				–0.8
Cell wall of mesophyll (at 10 m)	–0.8	–0.7	–0.2	0.1	
Vacuole of mesophyll (at 10 m)	–0.8	0.2	–1.1	0.1	
Leaf xylem (at 10 m)	–0.8	–0.8	–0.1	0.1	
Root xylem (near surface)	–0.6	–0.5	–0.1	0.0	
Root cell vacuole (near surface)	–0.6	0.5	–1.1	0.0	
Soil adjacent to root	–0.5	–0.4	–0.1	0.0	
Soil 10 mm from root	–0.3	–0.2	–0.1	0.0	

Relationship Between RH & Y_{H_2O}



$$RH\% = \frac{c_{wv}}{c_{wv(sat)}}.100$$

RH = Relative Humidity (%)
Cwv = water concentration (moles m^{-3})
Cwv(sat) = saturation water concentration (moles m^{-3})

Relationship Between RH & Ψ_{H_2O}

$$\psi_{H_2O} = \frac{RT}{V_w} \ln(RH)$$

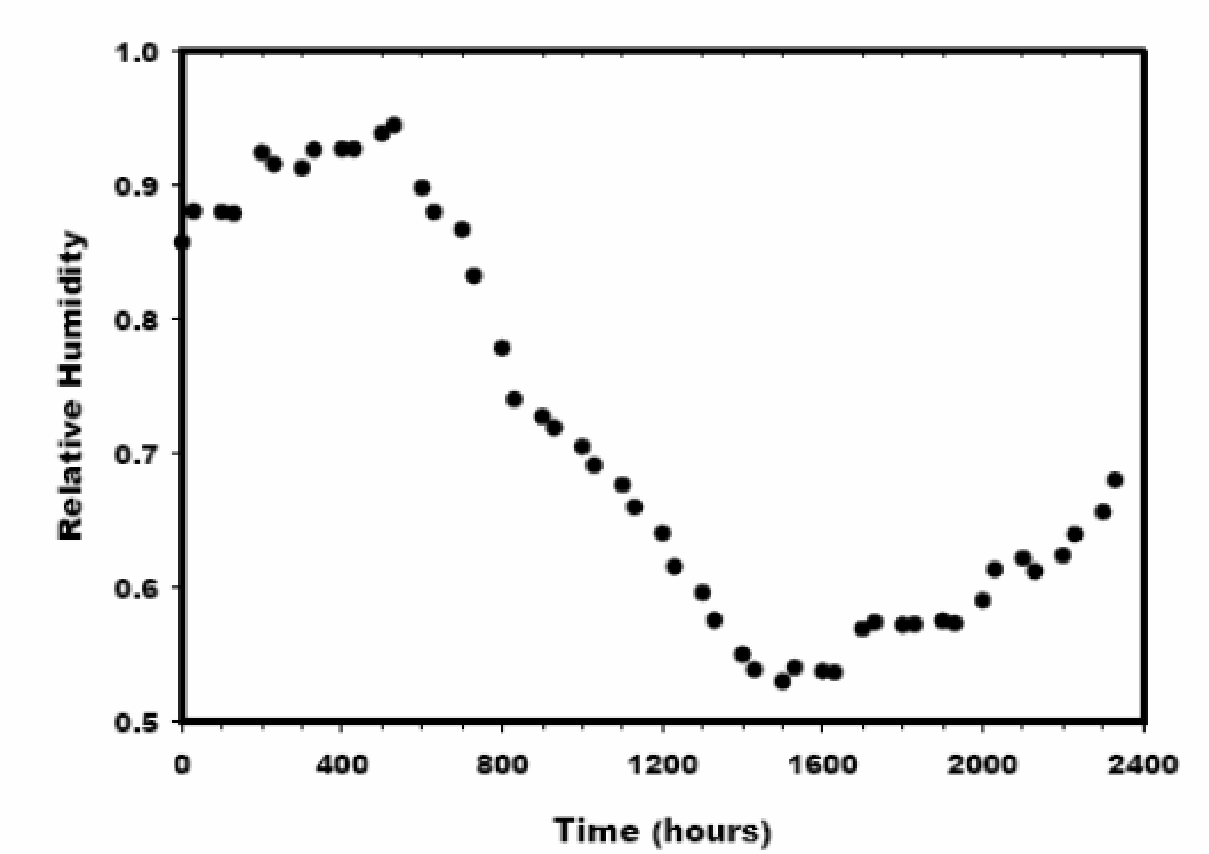
Ψw = water potential (kPa)
R = gas constant
= 8.314 kPa L mol^{-1} K^{-1}
T = temperature (^oK)
Vw = partial molal volume of water
= 0.018 Liters / mol
RH = relative humidity (0 - 1.0)
Note: MPa = kPa/1000

TABLE 4.2
Representative values for relative humidity, absolute water vapor concentration, and water potential for four points in the pathway of water loss from a leaf

Location	Relative humidity	Water vapor Concentration (mol m^{-3})	Water vapor Potential (MPa)[a]
Inner air spaces (25°C)	0.99	1.27	−1.38
Just inside stomatal pore (25°C)	0.95	1.21	−7.04
Just outside stomatal pore (25°C)	0.47	0.60	−103.7
Bulk air (20°C)	0.50	0.50	−93.6

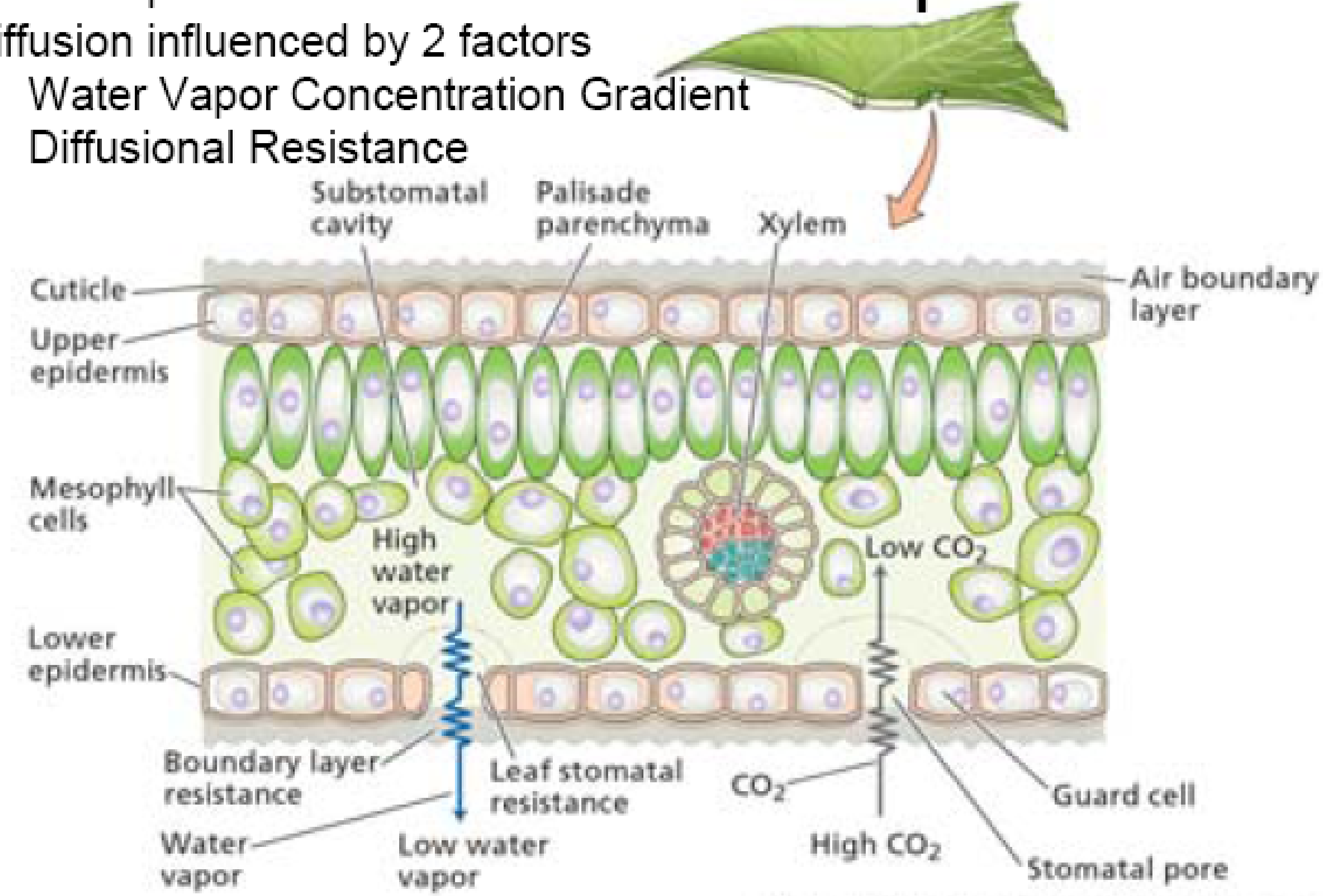
Source: Adapted from Nobel 1999.
Note: See Figure 4.10.
[a]Calculated using Equation 4.5.2 in Web Topic 4.5; with values for $RT/\bar{V}_w$ of 135 MPa at 20°C and 137.3 MPa at 25°C.

Diurnal Course of RH Over Crop Canopy

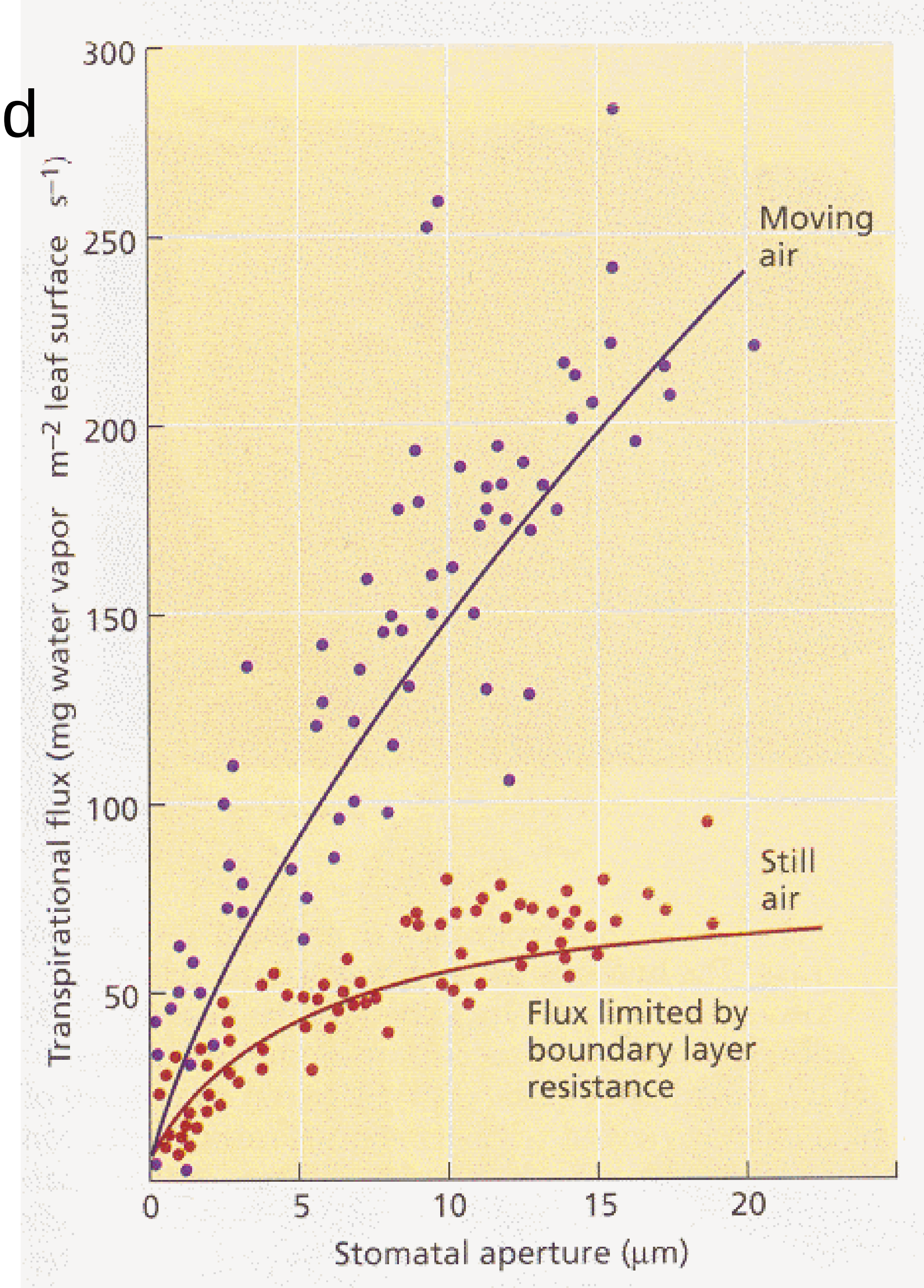


Water Movement from Leaf To Atmosphere

1. Water Vapor diffuses from Leaf to Air = **Transpiration**
2. Diffusion influenced by 2 factors
    1. Water Vapor Concentration Gradient
    2. Diffusional Resistance

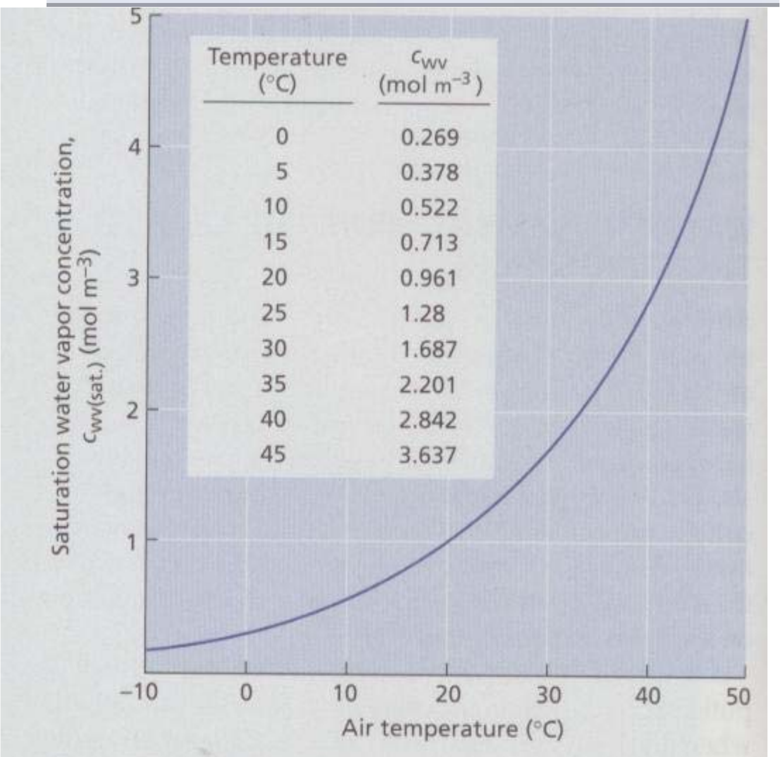


Stomatal Aperture And Boundary Layer Resistance At Leaf Surface



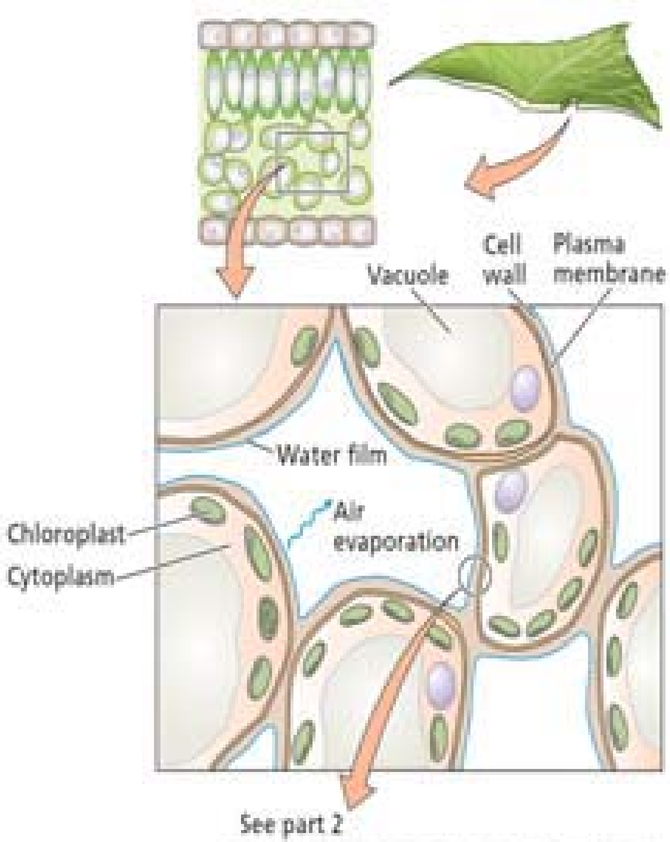
Role of Water Evaporation in Moving Water Up a Plant

Location	Relative humidity	Potential (MPa)[a]
Inner air spaces (25°C)	0.99	−1.38
Just inside stomatal pore (25°C)	0.95	−7.04
Just outside stomatal pore (25°C)	0.47	−103.7
Bulk air (20°C)	0.50	−93.6

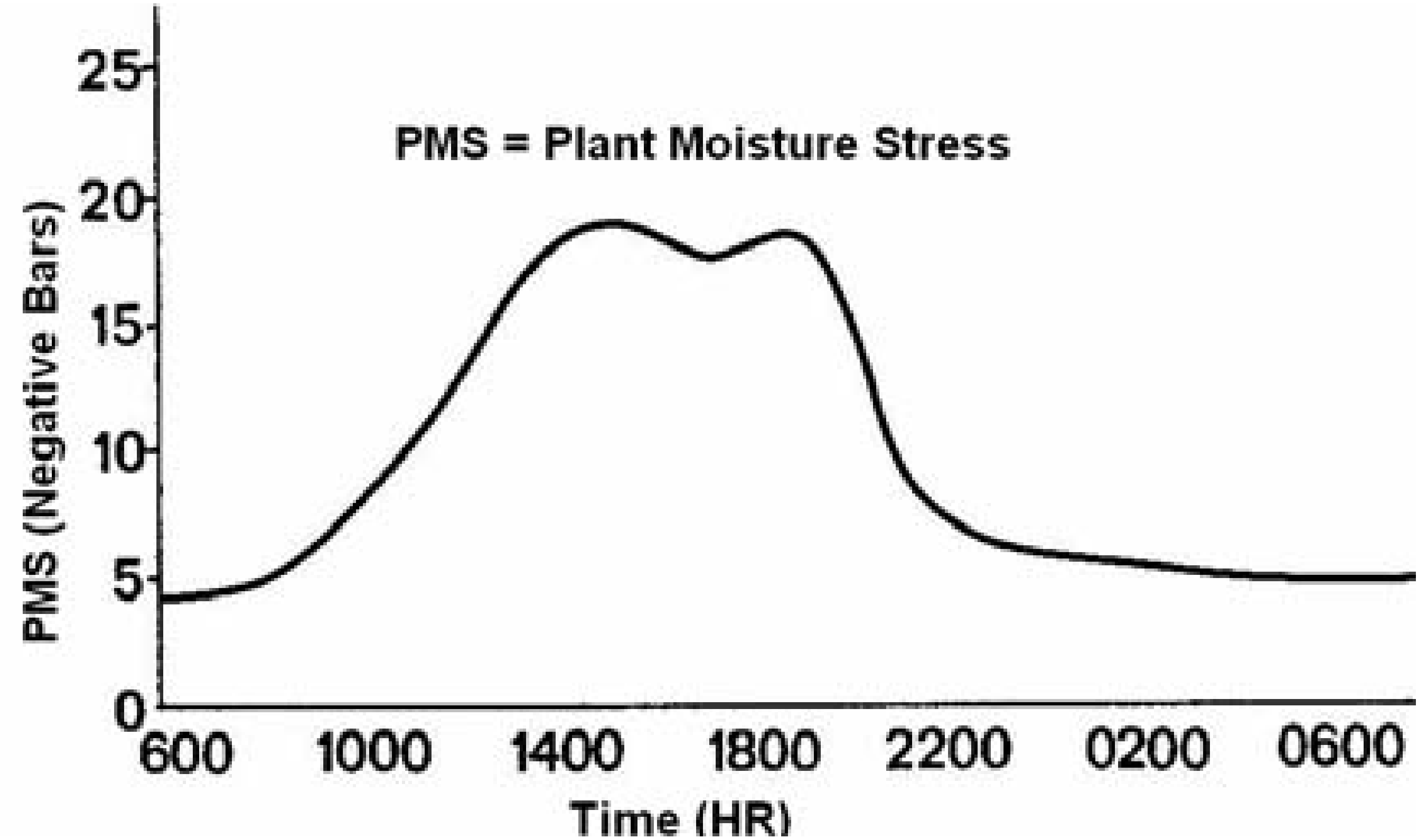


Temperature (°C)	c_{wv} (mol m^{-3})
0	0.269
5	0.378
10	0.522
15	0.713
20	0.961
25	1.28
30	1.687
35	2.201
40	2.842
45	3.637

FIGURE 4.11 Concentration of water vapor in saturated air as a function of air temperature.



Measuring Water Potential in Plants with a Pressure Chamber



Transpirational Water Losses

Plant Water Transpired (L) in Season

Potato 100

Winter wheat 100

Tomato 136

Corn 216

Silver Maple Tree 232 hr^{-1}

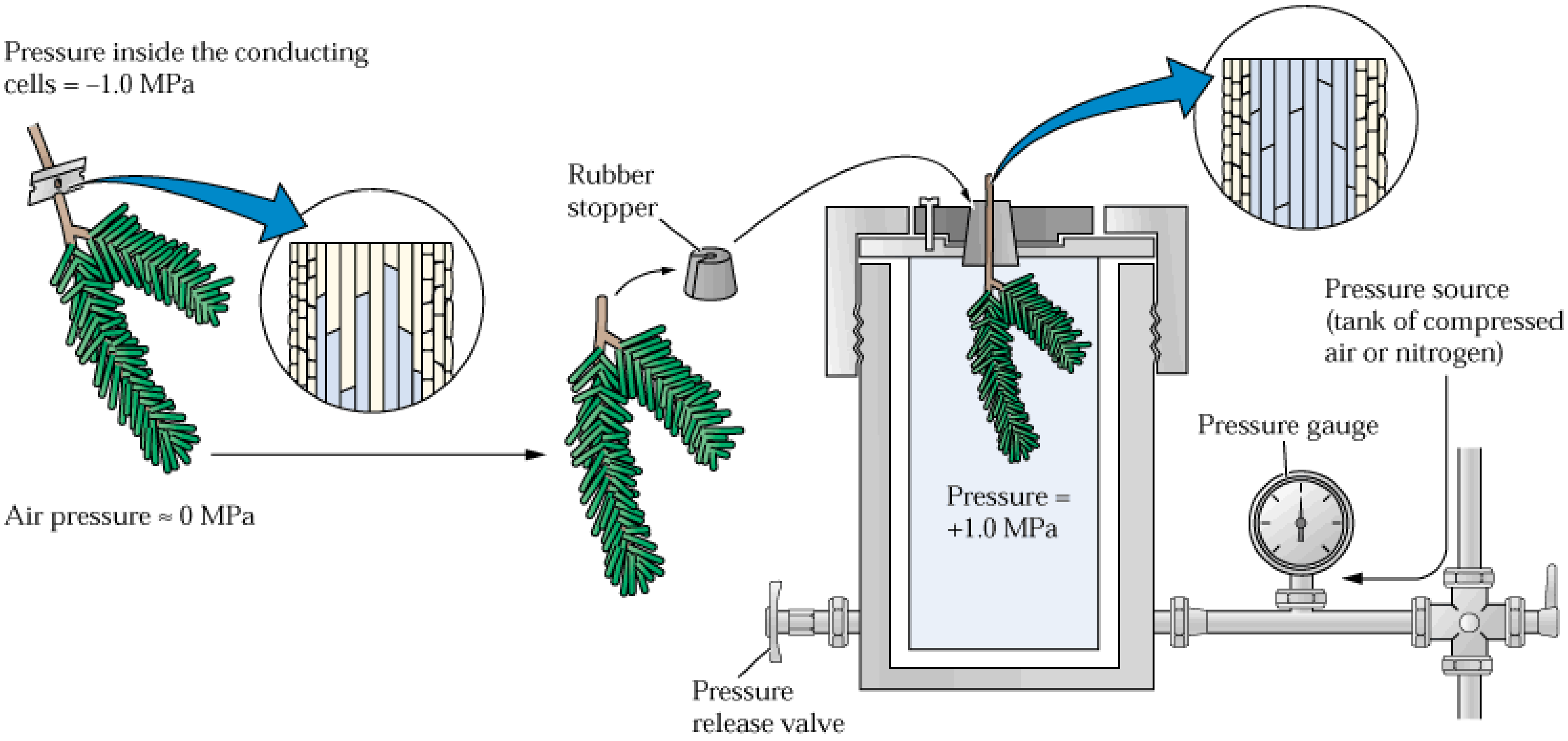
per kg corn grain 632

per kg corn plant 240

The Efficiency of Water Use Differs

Measuring Y_{H_2O}

1. Scholander's Pressure Chamber (Bomb)



Measuring Y_{H_2O}

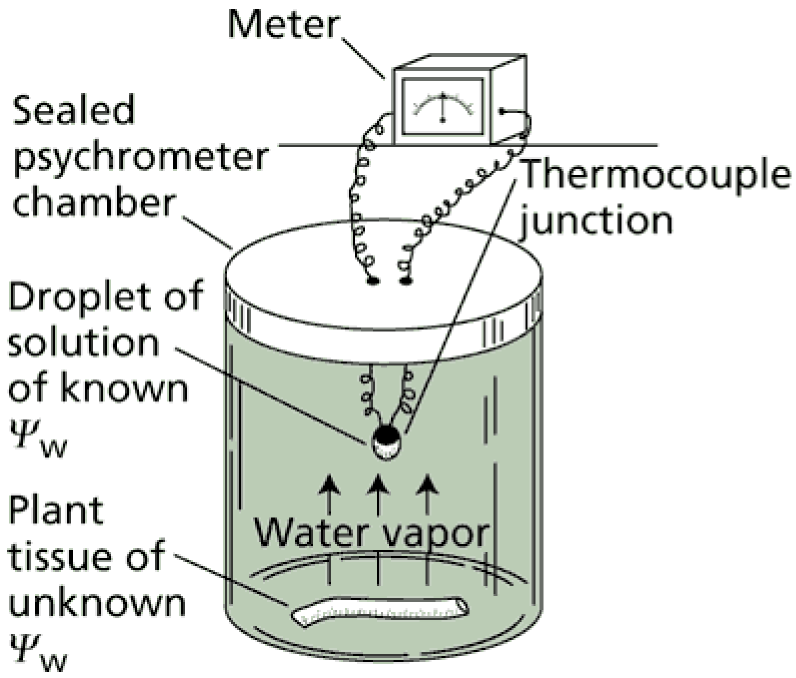
2. Psychrometer

Works by allowing tissue to come to equilibrium with a *SMALL* volume of air in a sealed chamber. Inside the chamber is a Thermocouple (temperature sensor) wetted with a drop of solution of known Y_{H_2O} .

If Y_{H_2O} Tissue more –ve than Y_{H_2O} Drop H_2O \
(latent heat of evaporation)

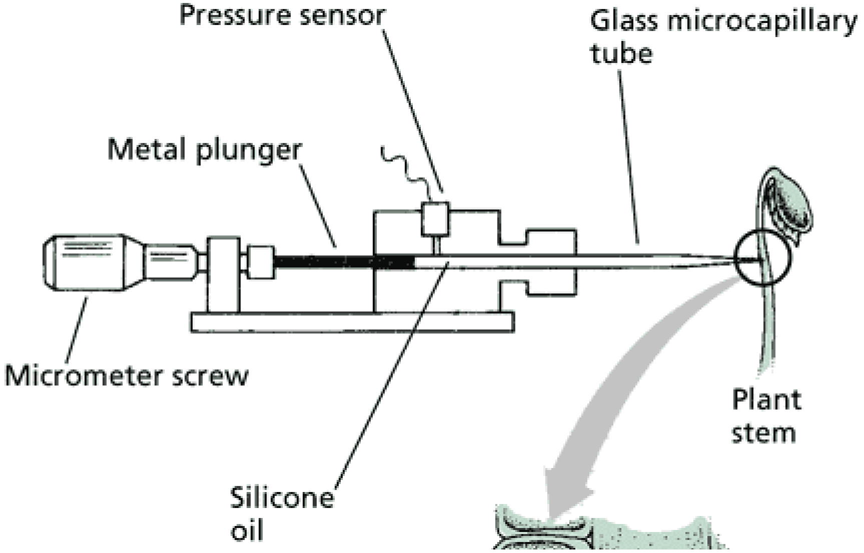
If Y_{H_2O} Tissue more +ve than Y_{H_2O} Drop H_2O \
(latent heat of evaporation)

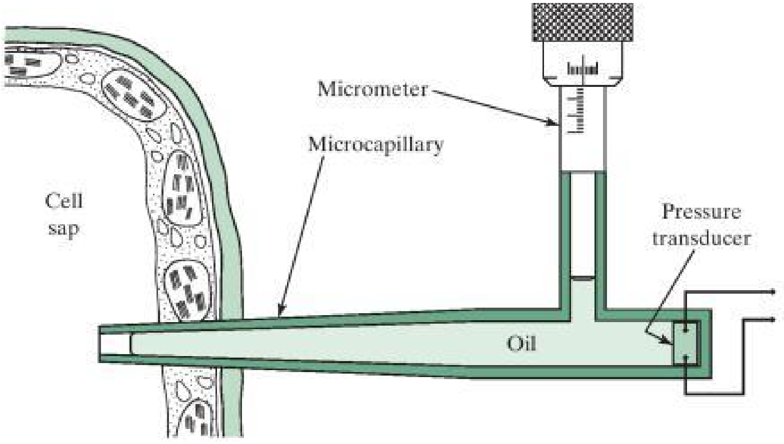
By plotting the rate of heat exchange on a gra
tissue YH_2O can be calculated.



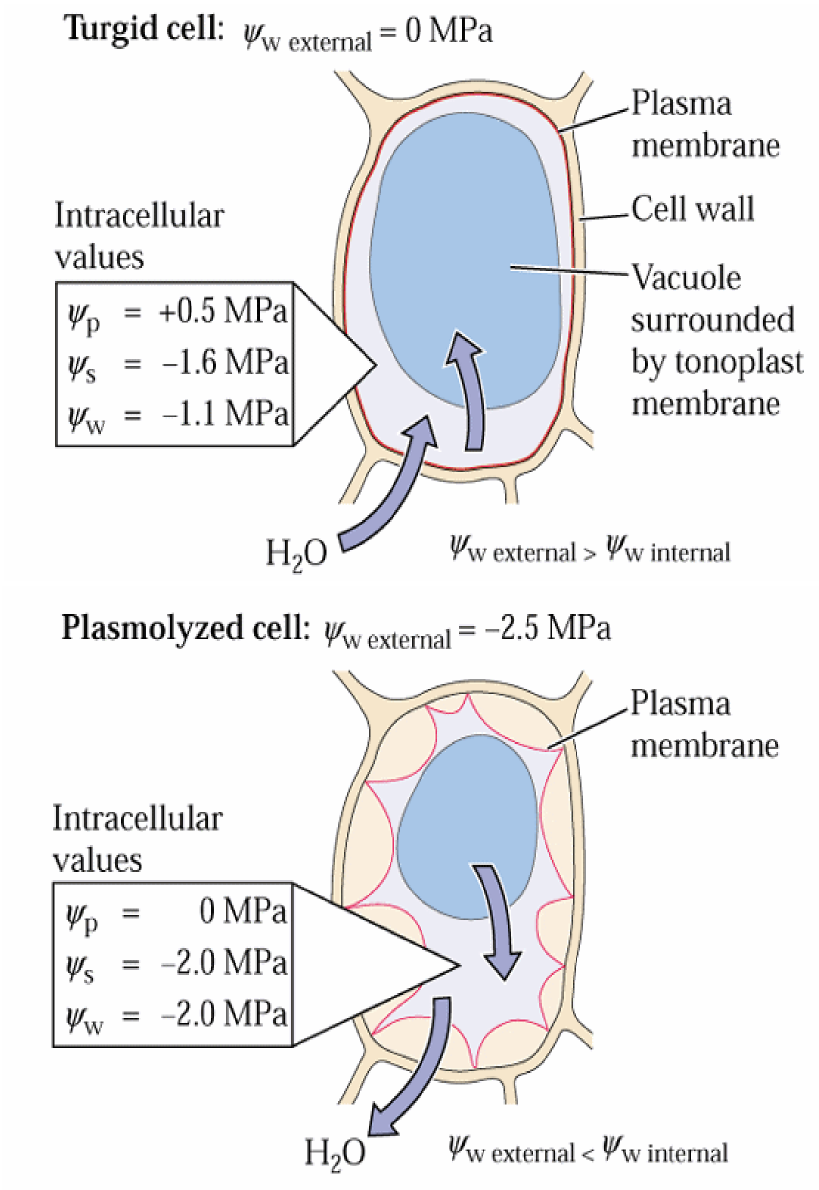
With some systems (e.g. Wescor C52), after deterr
frozen in liquid nitrogen to burst the cells and relea:
measured again to determine Y_s & Y_p can be founc

Turgor Pressure, Ψ_P, Can be Measured Directly with a Pressure Probe.





Many Abiotic Stress Factors Cause Water Stress

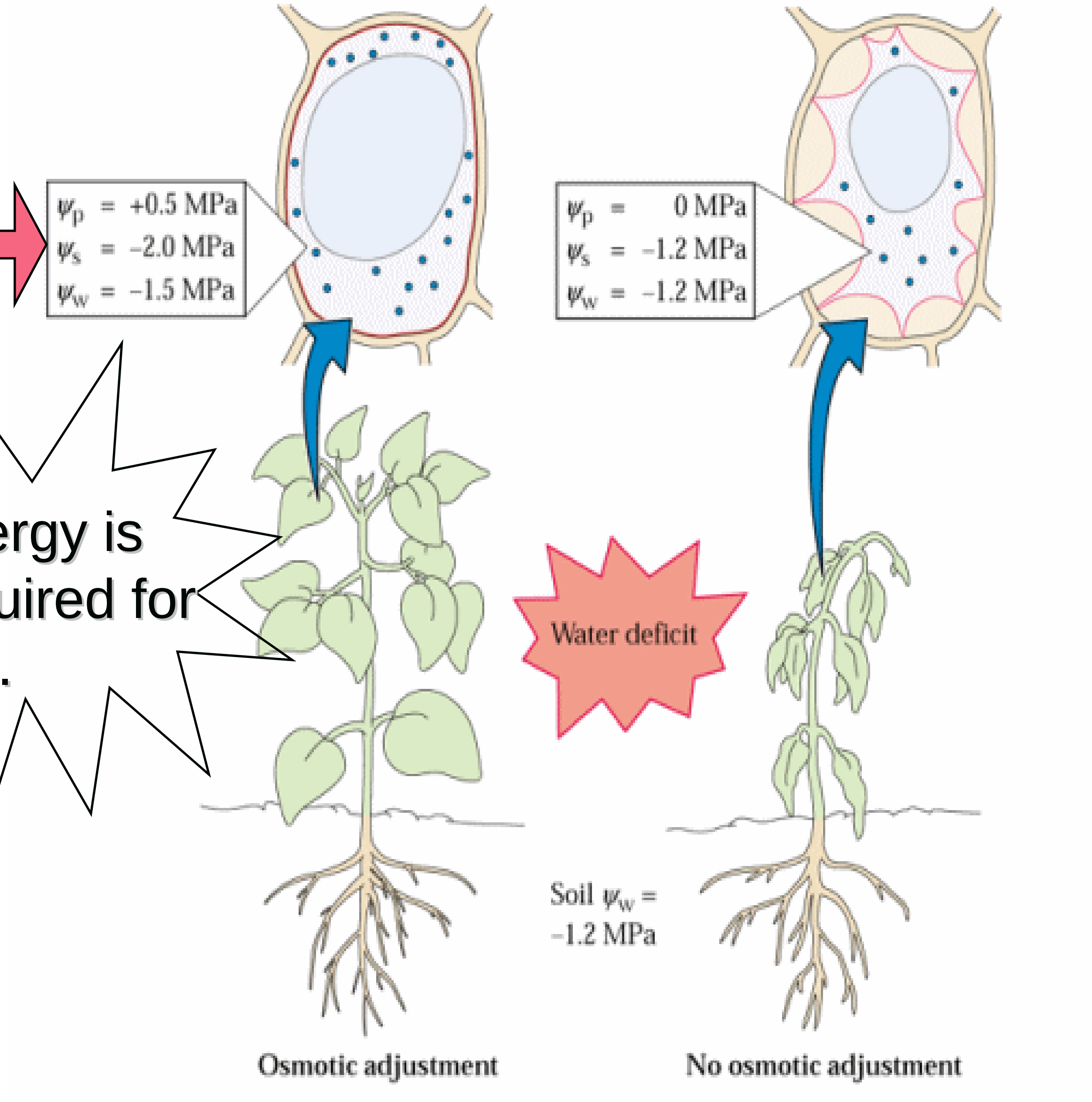


$$Y_w = Y_s + Y_p$$

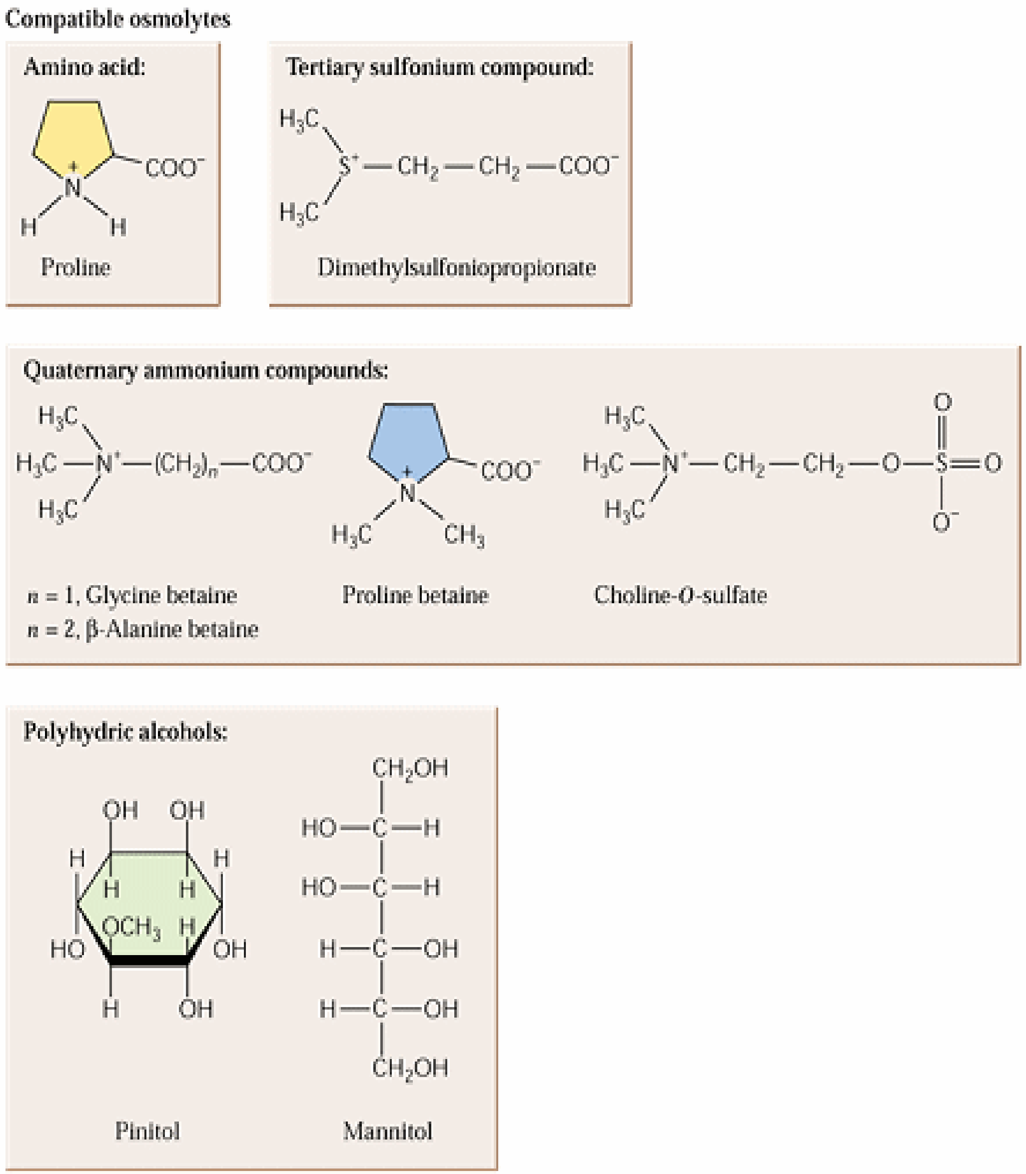
- Unless very low, low Y_w *per se* does not seriously affect plants
- But the loss of Y_p does! Y_p is required for:-
  - cell expansion (growth)
  - support in herbaceous plants

Osmotic Adjustment can Regain Y_p

Energy is required for this.

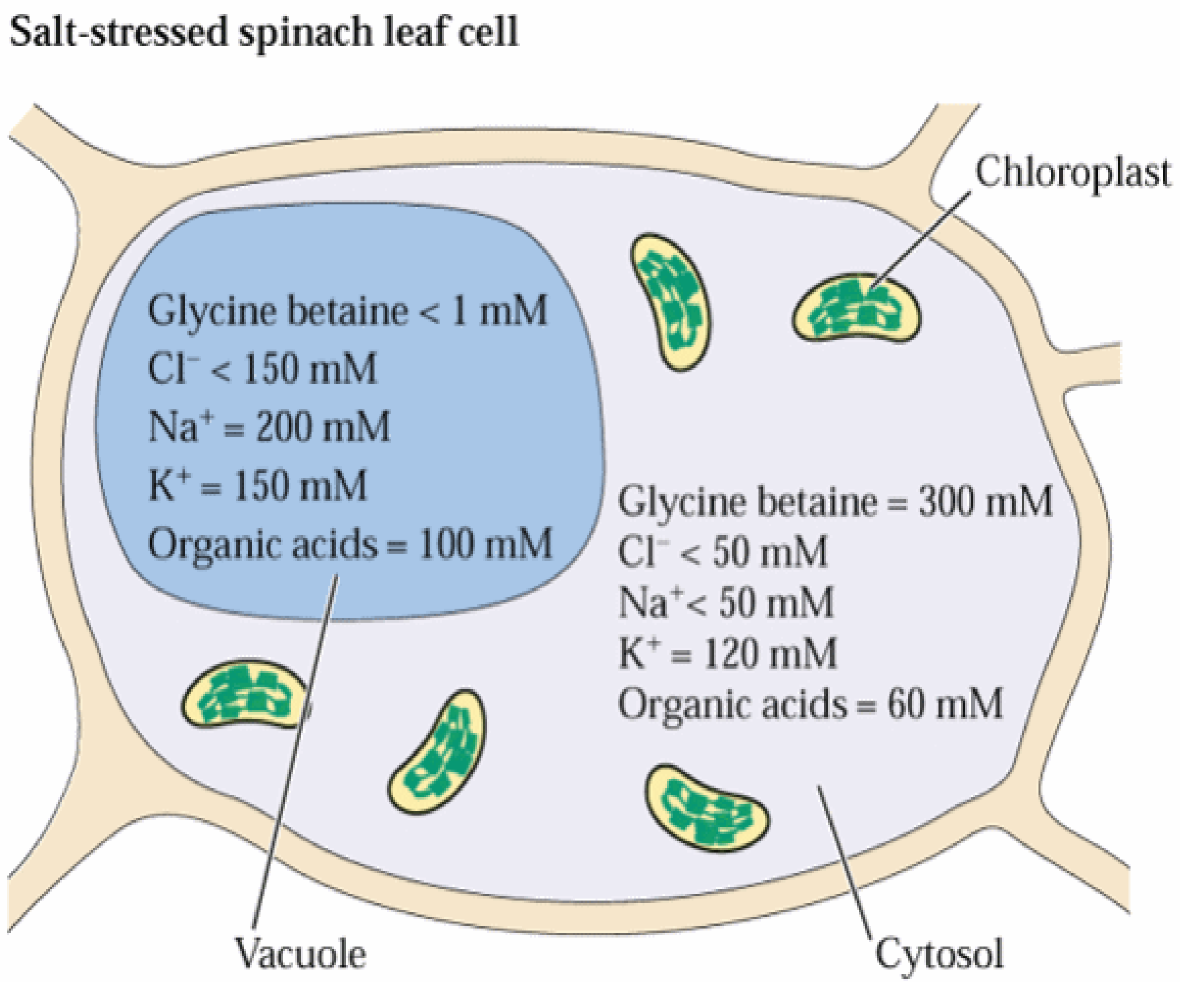


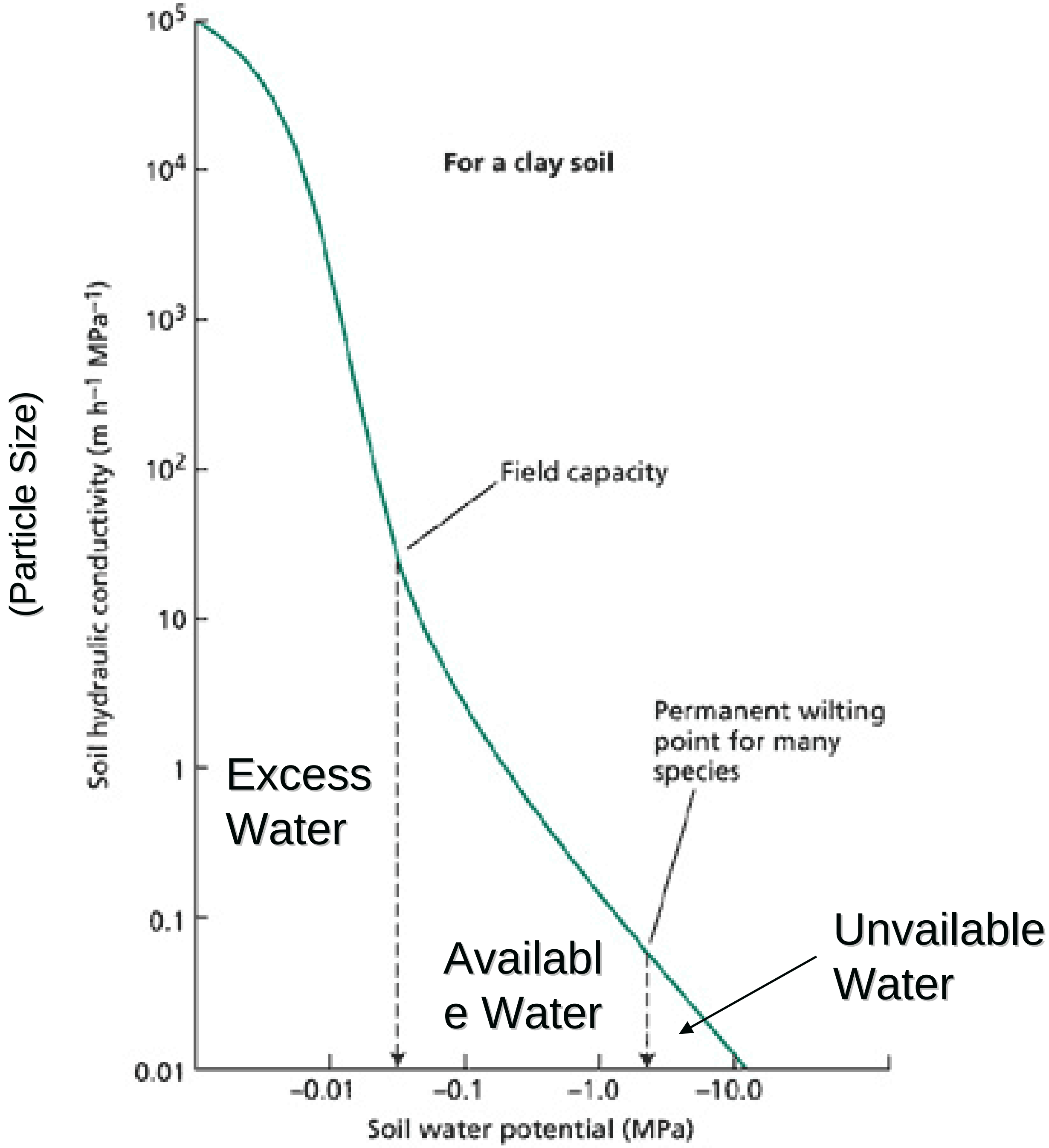
Plants Synthesize Compatible Solutes in Response to Water Stress



- Compatible solutes include:
  - Proline
  - Tertiary Sulfonium Compounds (TSCs)
  - Quaternary Ammonium Compounds (QACs)
  - Polyhydric alcohols

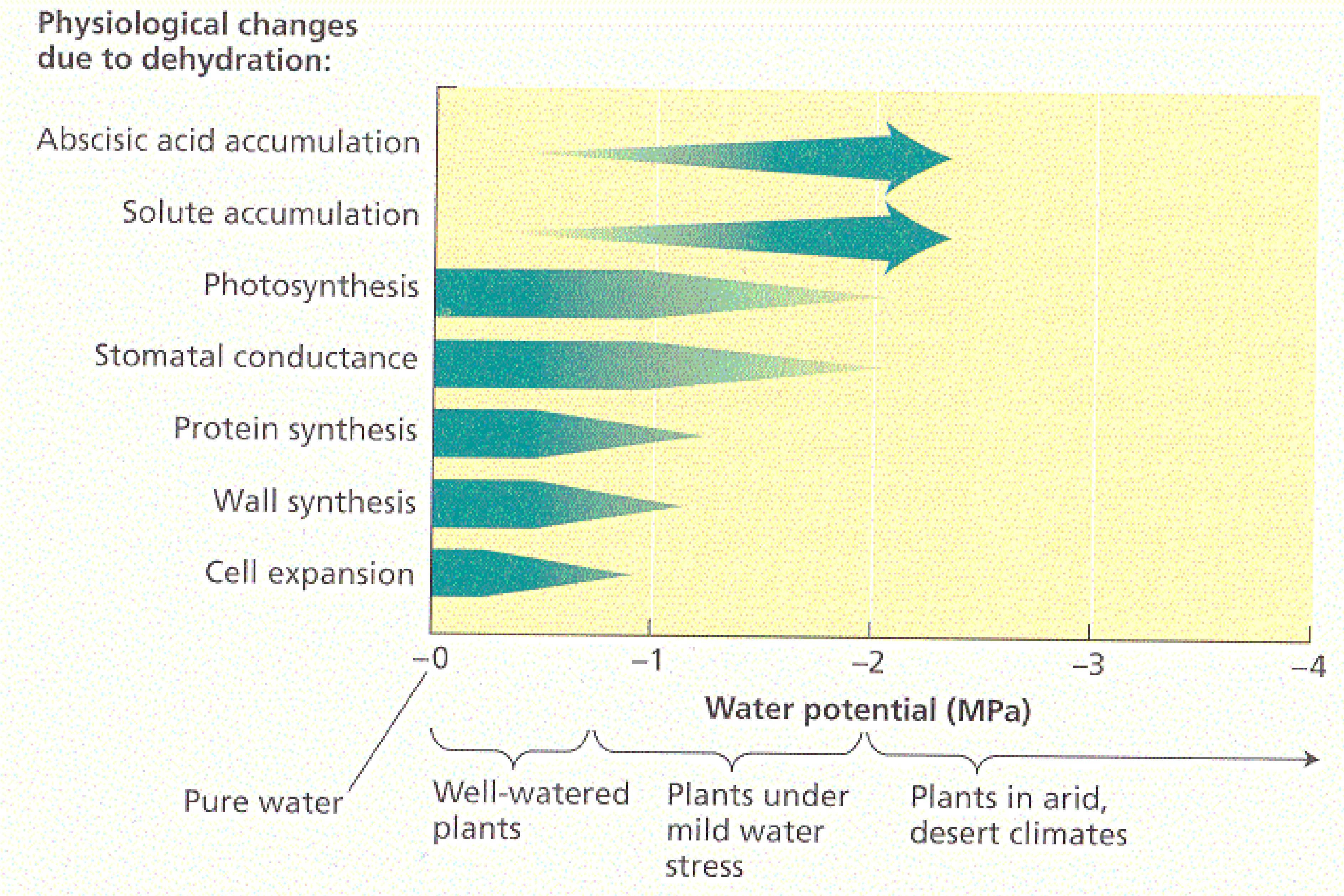
Compatible Solutes Accumulate in the Cytoplasm

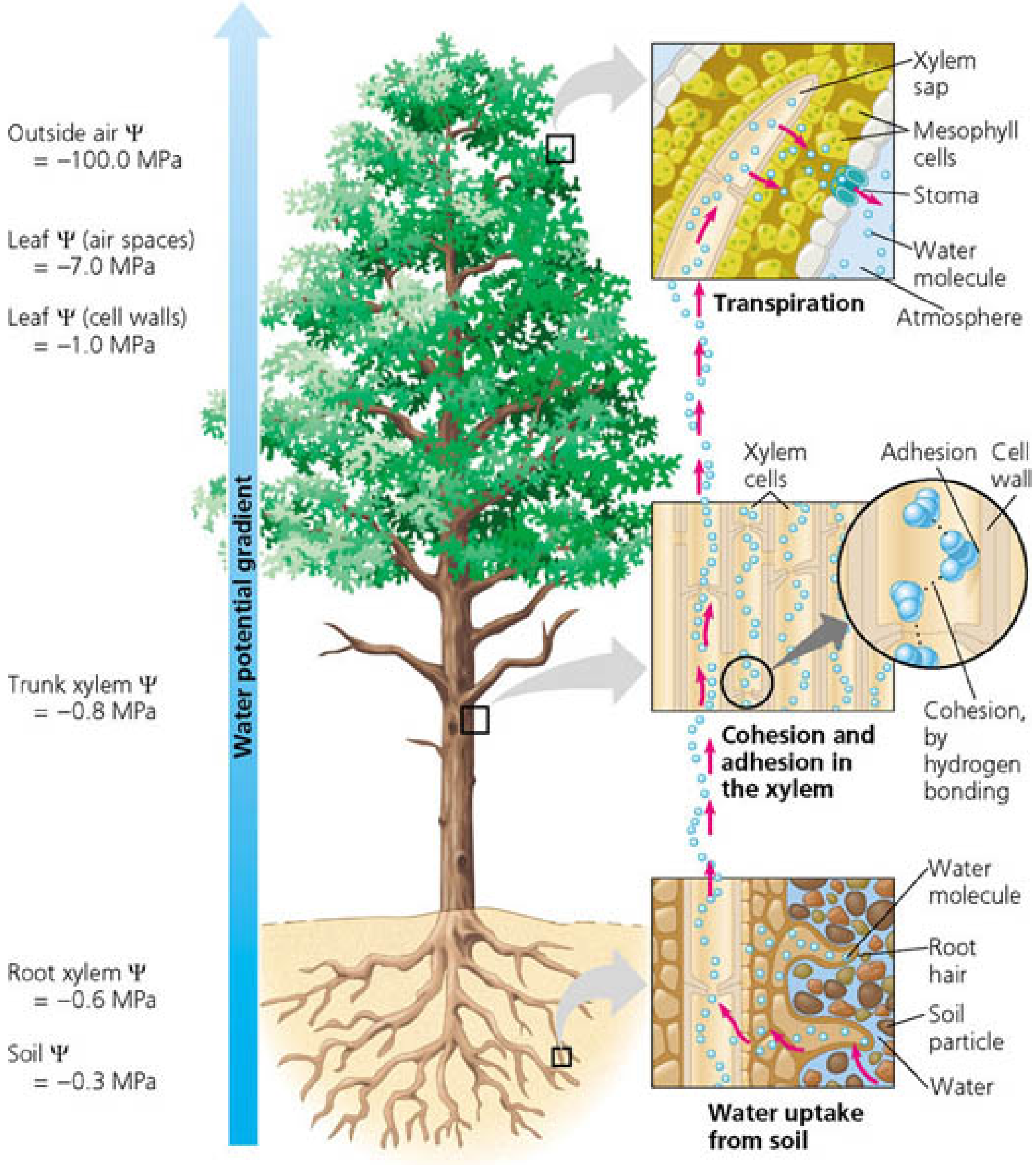




Field Capacity is the amount of water the soil can hold after drainage of excess water

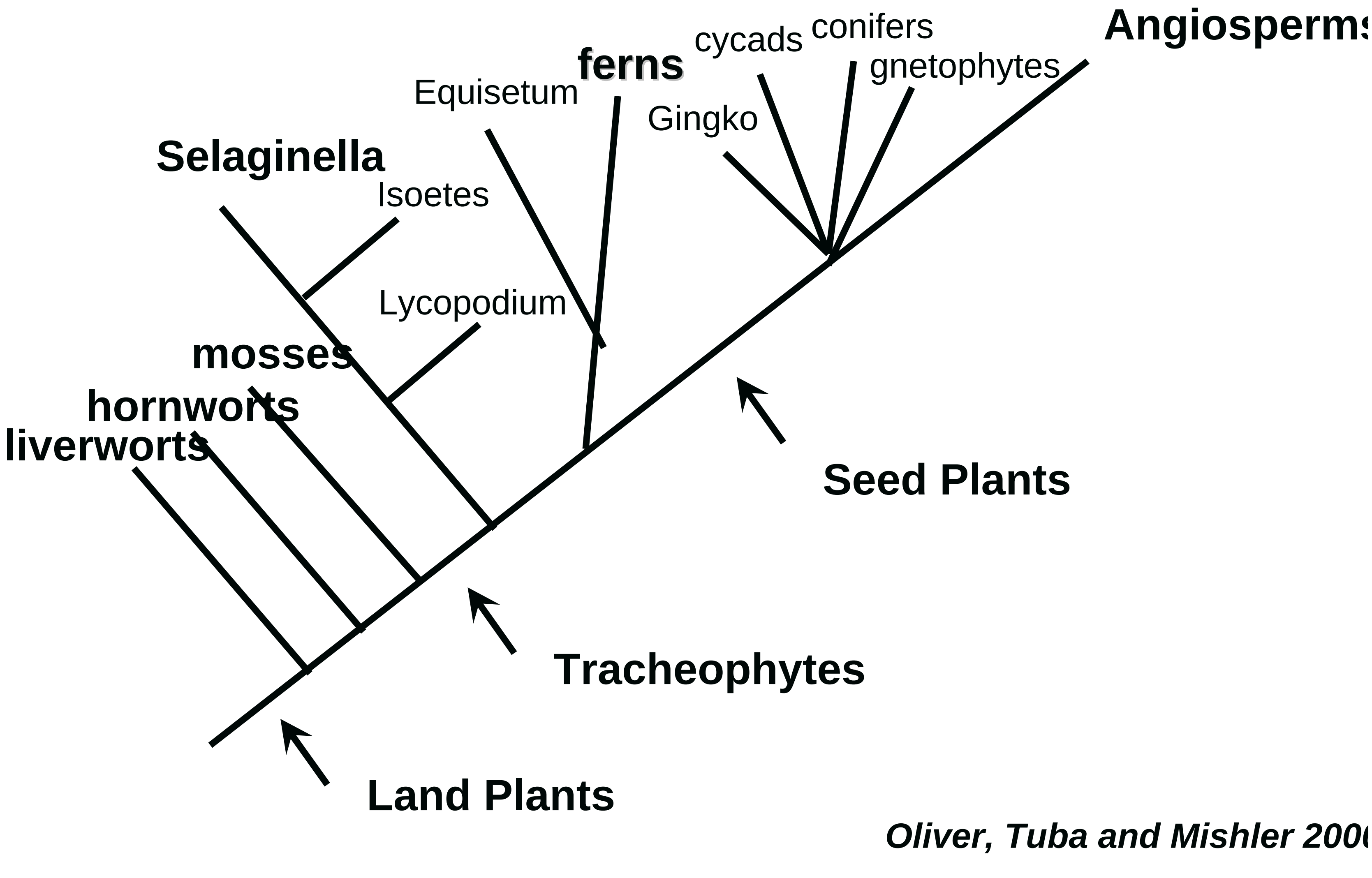
Permanent Wilting Point varies for different plants – Y_w beyond which turgor can not be regained,


Physiological changes due to dehydration:
Abscisic acid accumulation
Solute accumulation
Photosynthesis
Stomatal conductance
Protein synthesis
Wall synthesis
Cell expansion
−0
−1
−2
−3
−4
Water potential (MPa)
Pure water
Well-watered plants
Plants under mild water stress
Plants in arid, desert climates



Outside air Ψ
= −100.0 MPa
Leaf Ψ (air spaces)
= −7.0 MPa
Leaf Ψ (cell walls)
= −1.0 MPa
Trunk xylem Ψ
= −0.8 MPa
Root xylem Ψ
= −0.6 MPa
Soil Ψ
= −0.3 MPa
Water potential gradient
Xylem sap
Mesophyll cells
Stoma
Water molecule
Atmosphere
Transpiration
Xylem cells
Adhesion
Cell wall
Cohesion, by hydrogen bonding
Cohesion and adhesion in the xylem
Water molecule
Root hair
Soil particle
Water
Water uptake from soil

Distribution of Desiccation Tolerance in the Plant Kingdom



Bryophyte Model

RAPID WATER LOSS
Constitutive Cellular Protection

Hormone ?

Hydrated

Dry

Induction of
Recovery and Repa
Mechanisms

Rehydrated

Angiosperm Model

Hydrated

ABA

SLOW WATER LOSS
Induction of Cellular Protection

Dry

Re-establishme
Processes

Rehydrated

Orthodox Seeds

all angiosperm embryos can withstand desiccation!

Walters USDA NSSL Fort Collins

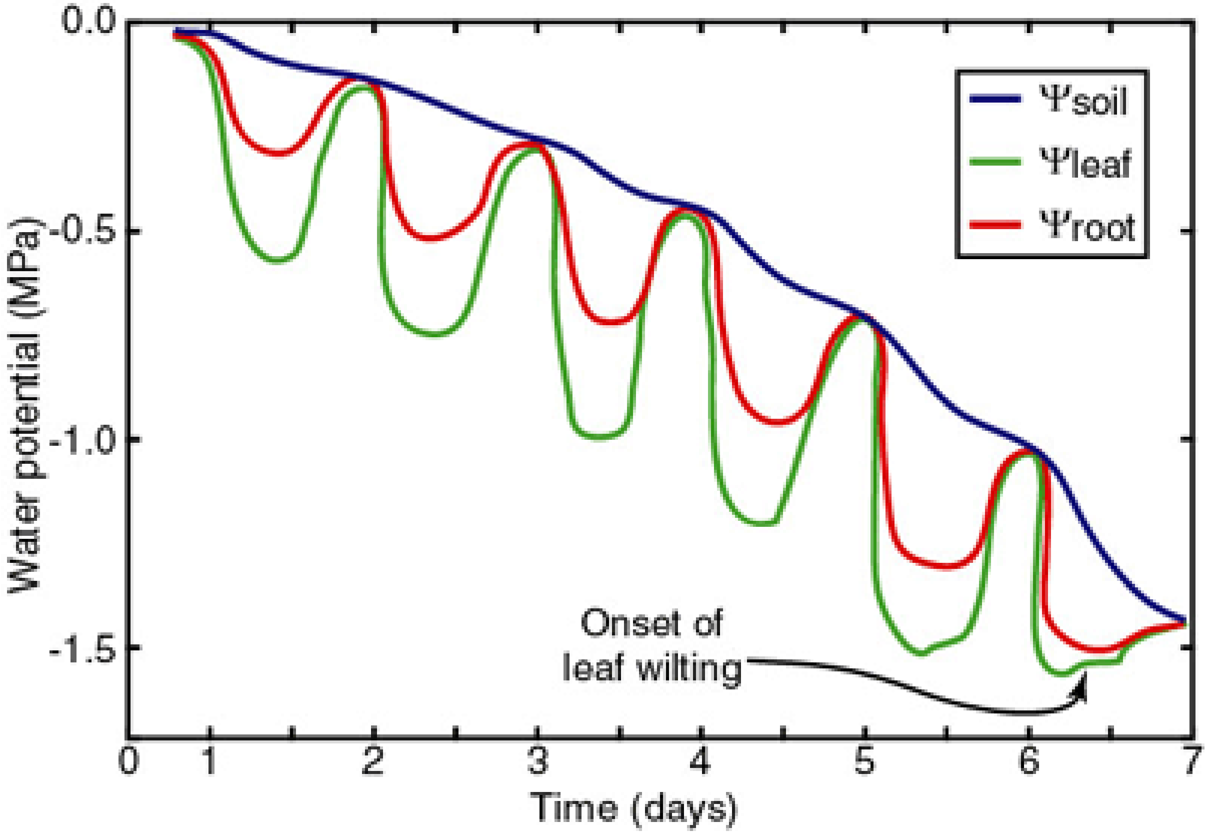
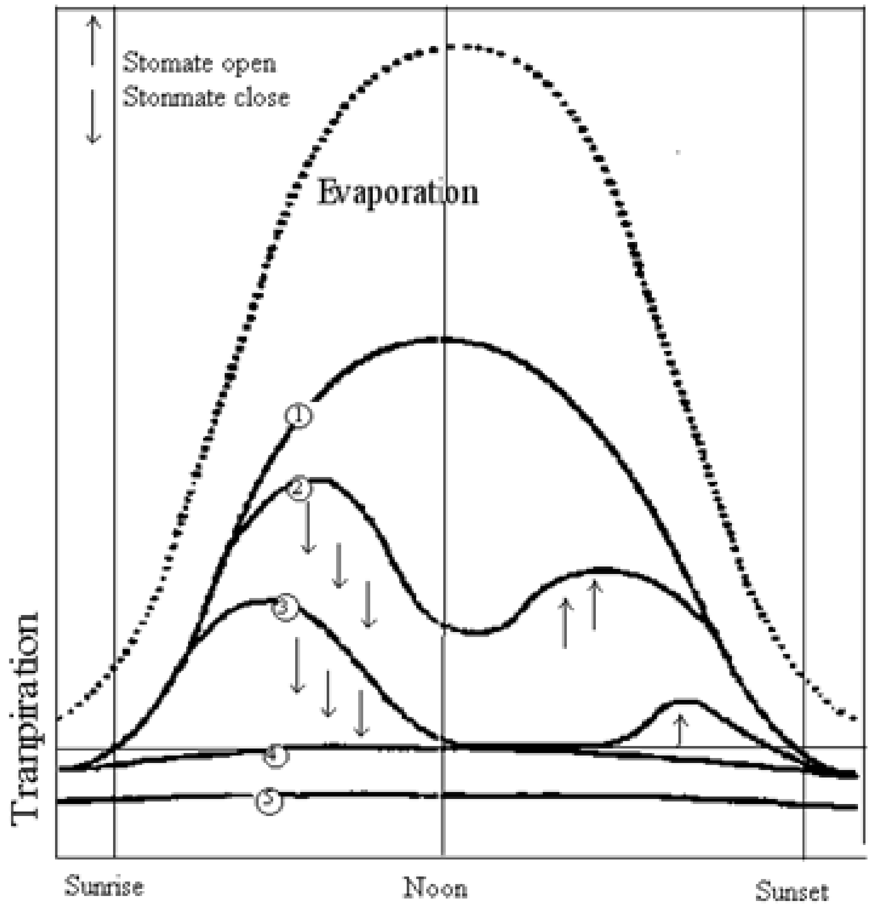


Figure 10.2. Schematic representation of daily changes in the water potential in the soil, root and leaf of a plant in an initially wet soil that dries out over a one week period. Shown are curves for the soil water potential, root xylem water potential and leaf (mesophyll) water potential, as adapted by Noble (1983; his figure 9.13) freely adapted from an article by Slatyer (1967, p 276).

Low Leaf Y_{H2O} can Lead to 'Mid-Day' Closure of Stomata

1. **no water limitation, stomates open**
2. **some water limitation midday stomatal regulation**
3. **severe water limitation midday stomatal closure**
4. **soil dry, complete stomatal closure**



Water Use in Plants: most is used in transpiration.

• **Photosynthesis**	**0.1 litres**
• **Growth**	
(new leaves, roots etc)	**1.9 litres**
• **Transpiration**	**98 litres**

Some Drought Tolerant Plants...How do they Survive?

Velloziaceae

Xerophyta villosa

Hamamelidae

Myrothamnus flabellifolia

Desiccation-tolerant Lilies

Laraea tridentata
Cresote Bush

Scrophulariaceae
Craterostigma plantagineum
(Resurrection Plant)

Hydrated

ABA

Dry

5 hours

Rehydrated

Desiccation-tolerant *Poaceae*

Xerophyta viscosa

Sporobolus stapfianus