Water & Plant Cells: Chapter 3

Why is water important?
1. 1g organic material requires 500g water.
2. Roles of water in plants (97% is lost)
   A. Solvent – Fluid medium for cytoplasm
   B. Photosynthesis
   C. Turgor pressure
   D. Transpiration & Heat dissipation
   E. Transport dissolved minerals
3. Productivity

Properties of Water
1. Hydrogen bonding
2. Excellent solvent – shells of hydration
3. Specific heat = 4.187kJ kg
4. Latent heat of vaporization = 44kJ mol
5. Cohesion, adhesion & capillarity
6. Surface tension
7. Tensile strength > 30MPa
   1 MPa = 1 newton m
   1 MPa = 1 Joule m
   1 MPa = 9.9 atmospheres
   1 MPa = 145.5 psi
   30 MPa = 4351 lb in

Major Processes Related to Water Movement in Plants
1. Short distance transport = Molecular Diffusion
2. Long distance transport = Bulk Flow

Processes of Water Movement in Plants
Short Distance Transport
1. Molecular Diffusion
   Fick's first law
   \[ J_s = \frac{-D_s \Delta c_s}{\Delta x} \]
2. Importance: Identifies factors governing short distance transport:
   1. Concentration gradient
   2. Distance
   3. Medium through which something moves

Long Distance Transport
Processes of Water Movement in Plants

Short Distance Transport

Influence of distance

1. Average time for a particle to diffuse

\[ \text{Average time} \propto \frac{L^2}{D} \]

\( L = \text{distance traveled} \)
\( D = \text{diffusion coefficient} \)

2. Example: Glucose travels

- 50\text{um} in 2.5 seconds
- 1 meter in 32 years

3. Point: Diffusion rapid over short distances very slow over long distances

Processes of Water Movement in Plants

Long Distance Transport

Bulk flow or Mass Flow

1. Molecules move in bulk driven by a pressure gradient.

\[ \text{Volume flow rate} = \frac{\pi r^4}{8 \eta} \frac{\nabla p}{\nabla x} \]

\( r = \text{radius of tube} \)
\( \eta = \text{viscosity of the liquid} \)
\( \nabla p = \text{pressure gradient} \)
\( \nabla x = \text{distance between gradient points} \)

2. Pressure driven bulk flow moves water long distances

Chemical Potential of Water

1. Free energy per mole of water

2. Water potential = \frac{\text{Chemical Potential}}{\text{Partial Molar Volume of water}}

3. Units of chemical/water potential

- Energy: J mol\(^{-1}\)
- Pressure: Pascal

4. The Pascal: 1 Pa = 0.000145 lb in\(^{-2}\)

- 1 MPa = 1,000,000 Pa
- 145 lb in\(^{-2}\)
- 10 bars
- 9.87 atmospheres

Pressure Units

<table>
<thead>
<tr>
<th>TABLE 3.1</th>
<th>Comparison of units of pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 atmosphere = 14.7 pounds per square inch</td>
<td></td>
</tr>
<tr>
<td>= 760 mm Hg (at sea level, 45° latitude)</td>
<td></td>
</tr>
<tr>
<td>= 1.013 bar</td>
<td></td>
</tr>
<tr>
<td>= 0.1013 Mpa</td>
<td></td>
</tr>
<tr>
<td>= 1.013 x 10(^3) Pa</td>
<td></td>
</tr>
</tbody>
</table>

A car tire is typically inflated to about 0.2 MPa. The water pressure in home plumbing is typically 0.2–0.3 MPa. The water pressure under 15 feet (5 m) of water is about 0.05 MPa.
Water Potential and Its Components

1. Water Potential Equation

\[ \psi = \psi_s + \psi_p + \psi_g \]

- \( \psi \) = water potential in MPa
- \( \psi_s \) = solute or osmotic potential
- \( \psi_p \) = pressure potential
- \( \psi_g \) = gravity potential

Solute or Osmotic Potential

1. Represents effect of solutes on water potential
2. Solutes always decrease water potential
   - Always reduce free energy of water
3. van't Hoff equation
   \[ \psi_s = -RTc_s \]
   - \( \psi_s \) = solute potential
   - \( R \) = gas constant (8.32 J mol\(^{-1}\) K\(^{-1}\))
   - \( T \) = temperature (degrees K)
   - \( c_s \) = solute concentration
     - (osmolal = moles solute per liter water)
4. Independent of solute identity

Values of Osmotic Potential

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>( R^\psi ) (L MPa mol(^{-1}))</th>
<th>0.01</th>
<th>0.19</th>
<th>1.00</th>
<th>Osmotic potential (MPa) of solution with solute concentration in mol L(^{-1}) water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.371</td>
<td>-0.0237</td>
<td>-0.127</td>
<td>-2.27</td>
<td>-3.6</td>
</tr>
<tr>
<td>20</td>
<td>2.478</td>
<td>-0.0244</td>
<td>-0.144</td>
<td>-2.44</td>
<td>-2.8</td>
</tr>
<tr>
<td>25</td>
<td>2.478</td>
<td>-0.0248</td>
<td>-0.148</td>
<td>-2.48</td>
<td>-2.8</td>
</tr>
<tr>
<td>30</td>
<td>2.529</td>
<td>-0.0252</td>
<td>-0.152</td>
<td>-2.52</td>
<td>-2.9</td>
</tr>
</tbody>
</table>

Note: \( R^\psi = 0.082143 \text{ L MPa mol}^{-1} \text{ K}^{-1} \).

Pressure Potential

1. Hydrostatic Pressure of solution
2. Turgor pressure = Positive hydrostatic pressure
3. Tension = Negative hydrostatic pressure
4. \( \psi_p = 0 \) in a standard state
Gravity Potential

1. Gravity causes water to move downward
2. \( \psi_g = \rho_w g h \)
   - \( \rho_w \) = density of water (1.0 kg/m\(^3\) at 4C)
   - \( h \) = height (meters)
   - \( g \) = acceleration due to gravity (9.8 ms\(^{-2}\))

\( \rho_w g = 0.01 \text{ MPa m}^{-1} \)

For a 100 meter tree: \( \psi_g = 0.01 \text{ MPa m}^{-1} \times 100 = 1.0 \text{ MPa} \)

1 MPa = 145 lb in\(^{-2}\)

5. Here's the point:
   - In cells: \( \psi_g \) is negligible (no change in height)
   - In tall trees (100 meters) = 1.0 MPa change in \( \psi_w \)

\( \psi_g = \text{Gravity Potential} \)

\( \psi_m = \text{Matric Potential} \)

1. Matric = surface which binds water
2. Can be strong or negligible
   - Negligible \( \rightarrow \) hydrated tissues
   - Strong \( \rightarrow \) dry surfaces (e.g. seeds)
   - Examples: Dry seed \( \psi \approx -50 \) to -350 MPa
   - Hydrated seed \( \psi \approx 0 \) MPa

3. Here's the point:
   - In hydrated tissue: \( \psi_g \) is negligible
   - In dry tissue: \( \psi_g \) is very important

4. Application \( \rightarrow \) Soil matric potential is a critical variable in crop yield, runoff, evapotranspiration and irrigation scheduling.

Numerical Examples of Water Potential & Its Components

- Pure water
- Solution containing 0.1 M sucrose
- Flexed cell dropped into sucrose solution
- Concentration of sucrose increased
Numerical Examples of Water Potential and Its Components

1. In a turgid cell, water potential drop results in sharp turgor drop with little change in cell volume.
2. As cell volume decreases below 90%, osmotic potential decreases faster than turgor (Turgor = 0) with further decline in water potential.

Sensitivity of Various Physiological Processes to Dehydration

END

Chapter 3
Water and Plant Cells
Chapter 4
Water Balance of Plants
Mechanisms & driving forces operating on water transport in plants

Components of soil water potential

\[ \psi_{\text{soil}} = \psi_s + \psi_p \]

\( \psi_p \) = about -2MPa in dry clay soil.
Permanent Wilting Point = \( \psi_{\text{soil}} > \psi_{\text{plant}} \)

<table>
<thead>
<tr>
<th>Soil</th>
<th>Particle diameter (μm)</th>
<th>Surface area per gram (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Course sand</td>
<td>200 - 20</td>
<td>&lt; 1 - 5</td>
</tr>
<tr>
<td>Fine sand</td>
<td>20 - 2</td>
<td>10 - 100</td>
</tr>
<tr>
<td>Silt</td>
<td>2 - 0.2</td>
<td>100 - 1000</td>
</tr>
<tr>
<td>Clay</td>
<td>2</td>
<td>1000 - 1000</td>
</tr>
</tbody>
</table>

Relative Size of soil particles

Field Capacity
- Clay soil: 40%
- Sand: 3%

Soil Hydraulic Conductivity

Soil hydraulic conductivity is how easily water moves through soil.
Role of Water Evaporation in Water Movement

<table>
<thead>
<tr>
<th>Radius of curvature (μm)</th>
<th>Hydrostatic pressure (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A) 0.5</td>
<td>-3</td>
</tr>
<tr>
<td>(B) 0.05</td>
<td>-15</td>
</tr>
<tr>
<td>(C) 0.01</td>
<td>-15</td>
</tr>
</tbody>
</table>

\[ \Psi_p = -\frac{2T}{r} \]

- \( T = \) surface tension of water
- \( T = 7.28 \times 10^{-8} \) MPa m
- \( r = \) radius of curvature

Water Movement: Soil to Root

- Root Hairs increase surface area.
- Concave menisci form at soil-water interface, creating very negative matric potentials.
- More water removed
- More acute menisci
- More negative \( \Psi_{\text{soil}} \)

Water Uptake by the Root

Water Absorption: Root

- Aquaporins regulate water movement through endodermis.
- Epidermis
- Cortex
- Pericycle
- Xylem
- Phloem
- Casparian strip
- Symplastic and transmembrane pathways
- Apoplast pathway
How does water move up a tree?

1. Diffusion
2. Capillarity
3. It’s pushed up
4. It’s pulled up

Processes of Water Movement in Plants

**Diffusion is a very slow process**

1. Average time for a particle to diffuse

\[
\frac{L^2}{D} \propto T
\]

- \(L = \) distance traveled
- \(D = \) diffusion coefficient

2. Example: Glucose travels
   - 50um in 2.5 seconds
   - 1 meter in 32 years

3. Point: Diffusion rapid over short distances
   Very slow over long distances

**Role of Aquaporins in water transport**

**Root Pressure and Guttation**
Could capillarity generate the force needed to draw water up a tree?

To calculate the height liquid can be raised by capillarity:

\[ h = \frac{2T \cos \theta}{\pi d g r} \]

- \( h \) = height of capillary (meters)
- \( T \) = surface tension (@20°C, \( T \) for water = 0.0728 Nm⁻¹)
- \( \cos \theta \) = 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)

### Capillarity as a Mechanism of Long Distance Water Transport

<table>
<thead>
<tr>
<th>Capillary diam (µm)</th>
<th>height of water column (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>3000</td>
</tr>
<tr>
<td>1</td>
<td>15.3</td>
</tr>
<tr>
<td>10</td>
<td>1.53</td>
</tr>
<tr>
<td>40</td>
<td>0.38</td>
</tr>
</tbody>
</table>

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

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**Xylem and Water Transport**

**Circular Bordered Pits**
Water Movement Through Xylem

- Requires less pressure than movement through cells
- From Pouiseullie's equation:

\[
\text{Volume flow rate} = \frac{\pi r^4}{8\eta} \frac{\Delta \psi}{\Delta x}
\]

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Pressure gradient (MPa m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xylem</td>
<td>0.02</td>
</tr>
<tr>
<td>Layer of cells</td>
<td>(2 \times 10^8)</td>
</tr>
</tbody>
</table>

Pressure Needed 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 Pressure to overcome
  - 100 meters × 0.01 MPa m⁻¹ = 1 MPa
- Total Pressure Needed = 3 MPa
Relative Humidity and Absolute Water Concentrations

\[ RH\% = \frac{C_{wv}}{C_{wv(sat)}} \times 100 \]

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

\[ \Psi_w = \frac{RT}{V_w} \ln(RH) \]

\( \Psi_w = \) water potential (kPa)
\( R = \) gas constant = 8.314 kPa L mol\(^{-1}\) K\(^{-1}\)
\( T = \) temperature (K)
\( V_w = \) 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

<table>
<thead>
<tr>
<th>Location</th>
<th>Relative Humidity</th>
<th>Concentration (mol m(^{-3}))</th>
<th>Potential (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner air spaces (25°C)</td>
<td>0.99</td>
<td>1.37</td>
<td>-1.38</td>
</tr>
<tr>
<td>Just inside stomatal pore (25°C)</td>
<td>0.95</td>
<td>1.21</td>
<td>-7.04</td>
</tr>
<tr>
<td>Just outside stomatal pore (25°C)</td>
<td>0.47</td>
<td>0.60</td>
<td>-163.7</td>
</tr>
<tr>
<td>Bulk air (20°C)</td>
<td>0.50</td>
<td>0.50</td>
<td>-93.6</td>
</tr>
</tbody>
</table>

Source: Adapted from Nobel 1999.
Note: See Figure 4.16.
*Calculated using Equation 4.5.2 in Web Topic 4.5, with values for \( \Psi_w \) of 110.8 kPa at 20°C and 137.3 kPa at 25°C.

**Diurnal course of Relative Humidity over a deciduous forest**

**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
Fig. 4.16 Soil-Plant-Atmosphere Continuum

<table>
<thead>
<tr>
<th>Location</th>
<th>Water potential ($\psi_w$)</th>
<th>Pressure potential ($\psi_p$)</th>
<th>Osmotic potential ($\psi_o$)</th>
<th>Gravity ($\psi_g$)</th>
<th>Water potential in gas phase ($\psi$ in mm $	ext{H}_2\text{O}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outside air (relative humidity = 50%)</td>
<td>-95.2</td>
<td></td>
<td></td>
<td></td>
<td>-95.2</td>
</tr>
<tr>
<td>Leaf internal air space</td>
<td>-0.8</td>
<td></td>
<td></td>
<td></td>
<td>-0.8</td>
</tr>
<tr>
<td>Cell wall of mesophyll at 10 m</td>
<td>-0.8</td>
<td>-0.7</td>
<td>-0.2</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Vacuole of mesophyll at 10 m</td>
<td>-0.8</td>
<td>0.2</td>
<td>-1.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Leaf xylem at 10 m</td>
<td>-0.8</td>
<td>-0.8</td>
<td>-0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Root xylem (near surface)</td>
<td>-0.6</td>
<td>-0.5</td>
<td>-0.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Root cell vacuole (near surface)</td>
<td>-0.6</td>
<td>0.5</td>
<td>-1.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Soil adjacent to root</td>
<td>-0.5</td>
<td>-0.4</td>
<td>-0.1</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>Soil 10 mm from root</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.1</td>
<td>0.0</td>
<td></td>
</tr>
</tbody>
</table>

Experimental Demonstration of Water Under Tension

1. Dye uptake in cut stems
2. Change in stem diameter (Fritts 1958 – Beech Trees)
3. Direct measurement – Pressure bomb
Measuring Water Potential in Plants with a Pressure Bomb

PMS = Plant Moisture Stress

Guard Cells Control Short Term Regulation of Water Loss

1. Turgor increase in guard cell solute concentration ... pores open
2. Turgor decrease in guard cell solute concentration ... pores close

Physical Challenges of Cohesion
Tracheary Elements are connected by Pits

Physical Challenges of Cohesion-Tension

1. Break strength of water is \( \approx 30 \text{MPa} \)
   \(< \text{Pressure needed to raise water.} \)
2. Water in a metastable state
   \(-3 \text{MPa} \approx -30 \text{Atmospheres} \)
3. Cavitation or embolism
   A. Controlled by
      Redissolving trapped gas
   B. Secondary growth replaces xylem
Physical Challenges of Cohesion-Tension

Pit pairs regulate embolism

Transpirational Water Loss

<table>
<thead>
<tr>
<th>Plant</th>
<th>Water transpired</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potato</td>
<td>25 gallons</td>
</tr>
<tr>
<td>Winter wheat</td>
<td>25 gallons</td>
</tr>
<tr>
<td>Tomato</td>
<td>34 gallons</td>
</tr>
<tr>
<td>Corn</td>
<td>54 gallons</td>
</tr>
<tr>
<td>Silver Maple Tree</td>
<td>58 gallons hr⁻¹</td>
</tr>
<tr>
<td>per kg corn grain</td>
<td>600 kg (about 158 gallons)</td>
</tr>
<tr>
<td>per kg corn plant</td>
<td>225 kg (about 60 gallons)</td>
</tr>
</tbody>
</table>

Species vary in xylem hydraulic conductivity

Drought Tolerance
Water Transport in Mangroves

Mangroves in Esmeraldas, Ecuador, Majagual Region.

Florida Mangroves

Water Transport in Mangroves

- Leaf Cells: \( \Psi = -2.7 \text{ MPa} \)
  - \( \Psi_B = 0.5 \text{ MPa} \)
  - \( \Psi_B = -3.2 \text{ MPa} \)

- Stem Xylem:
  - \( \Psi = -2.6 \text{ MPa} \)
  - \( \Psi_B = -2.5 \text{ MPa} \)
  - \( \Psi_B = -0.1 \text{ MPa} \)

- Root Cortex Cells: \( \Psi = -2.7 \text{ MPa} \)

- Salt Water:
  - \( \Psi = -2.4 \text{ MPa} \)
  - \( \Psi_B = 0 \text{ MPa} \)
  - \( \Psi_B = -2.4 \text{ MPa} \)

Air Temp = 20°C
RH = 50%
\( \Psi = -94.3 \text{ MPa} \)

END

Water Balance of Plants