CO₂

Water movement through the soil-plant continuum

Plant Ecology in a Changing World
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Part 1
Critical features essential to plant invasion of land
Land plants evolved from aquatic algae

The transition to land created numerous benefits and challenges
Plants evolved a cuticle and stomata to regulate gas exchange, which prevented leaves from drying out.
Part 2
Water moves along gradients of decreasing water potential
Plants tend to lose water when taking in CO$_2$

Ohm’s Law analogy

\[ A = g_{CO2}(c_a - c_i) \]

\[ E = g_{H2O}(e_i - e_a) \]

\[ g_{CO2} = g_{H2O}/1.6 \]
Water moves through soils and plants:
- as a liquid
- by bulk flow
- along gradients of decreasing water potential

Taiz & Zeiger 2010
Water along gradients of deceasing total water potential

\[ \Psi_{\text{total}} = \Psi_{\text{pressure}} + \Psi_{\text{osmotic}} + \Psi_{\text{matric}} + \Psi_{\text{gravitational}} \]

\[ \Psi_{\text{total}} = 0 \]

pure, free water at ground level and atmospheric pressure

Plants generally have negative \( \Psi \) values.
The unit is MPa (or historically bars)
\[ \Psi_{\text{total}} = \Psi_{\text{pressure}} + \Psi_{\text{osmotic}} + \Psi_{\text{matric}} + \Psi_{\text{gravitational}} \]

**Diagram:**
- **Cell Wall:** Semi-permeable
- **Cell Membrane:**
  - \( \Psi_o = -1 \)
  - \( \Psi_T = -1 \)
  - \( \Psi_o = 0 \)
  - \( \Psi_T = 0 \)
- **Non-equilibrium Starting Condition**
\[ \Psi_{\text{total}} = \Psi_{\text{pressure}} + \Psi_{\text{osmotic}} + \Psi_{\text{matric}} + \Psi_{\text{gravitational}} \]
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\[ \Psi_{\text{total}} = \Psi_{\text{pressure}} + \Psi_{\text{osmotic}} + \Psi_{\text{matric}} + \Psi_{\text{gravitational}} \]

\[ \Psi_g = \rho gh \approx 0.01 \text{ MPa m}^{-1} \]

(1 MPa = 145 psi)
Matric potential is capillary forces (most relevant for water in soil)
narrower capillaries = stronger forces

\[ \Psi_{\text{total}} = \Psi_{\text{pressure}} + \Psi_{\text{osmotic}} + \Psi_{\text{matric}} + \Psi_{\text{gravitational}} \]

adhesion + cohesion
Matric potential is capillary forces

narrower capillaries = stronger forces

\[ \Psi = \Psi_m + \Psi_o + \Psi_g \]

\( \Psi_m = \frac{-2\sigma \cos \alpha}{r} \)

\[ \Psi_1 = \Psi_0 - \rho gh \]

\[ \Psi_0 = 0 \]
Water is held in capillaries between soil particles

smaller particles house smaller capillaries

water evaporates from larger capillaries first, leaving more tightly held water in smaller capillaries

water potential decreases

Nobel 2009
Soil type influences matric potential

Campbell & Norman 1998
Part 3
Water moves from soil to leaves under tension (negative pressure)
How do plants pull water from the soil?

http://biobook.nerinxhs.org/bb/special_topics/microscopy/plantanatomy/syringaleafplabeled.htm
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How do plants pull water from the soil?

Water transport is driven solely by evaporation from cell walls.

- 10 nm
- -29 MPa

http://biobook.nerinxhs.org/bb/special_topics/microscopy/plantanatomy/syringaleafplabeled.htm
A range of minimum total water potentials in chaparral species
A range of minimum water potentials in chaparral species

Xylem water is commonly beyond its boiling point

Jacobsen et al 2007 Ecol Mono
Part 4
Plants have evolved features to reduce cavitation
Conduits cavitate when air enters from embolized conduits
Two inter-conduit check valve types

Pittermann et al. 2006 Science
Vulnerability curves quantify resistance to xylem cavitation

Sperry 2000 AgForMet
How do we typically measure total water potential?

Water is under tension (negative pressure). In a pressure chamber, positive pressure is added until water appears at the cut surface.
At equilibrium and without transpiration:

$$\Psi_{leaf} = \Psi_{soil} - \rho gh$$
without transpiration:  \[ \Psi_{leaf} = \Psi_{soil} - \rho gh \]

with transpiration:  \[ \Psi_{leaf} = \Psi_{soil} - \rho gh - \frac{Q}{k} \]

\[ Q = k(\Delta \Psi - \rho gh) \]
without transpiration:

\[ \Psi_{\text{leaf}} = \Psi_{\text{soil}} - \rho gh \]

with transpiration:

\[ \Psi_{\text{leaf}} = \Psi_{\text{soil}} - \rho gh - \frac{Q}{k} \]

\[ Q = k(\Delta \Psi - \rho gh) \]

\[ (E = 1.6g(e_i - e_a)) \]
Gas exchange with the environment and internal water transport are coupled

\[ Q = k(\Delta \Psi - \rho gh) \]

\[ Q = E \times \text{leaf area} \]

\[ E = 1.6g(e_i - e_a) \]

\[ A = g(c_a - c_i) \]
Hydraulic conductance depends on the path of water flow
When plants lack a conducting system, plants are small and water movement from source to the environment through plants is slow.
The evolution of xylem greatly increased hydraulic conductance ($k$).

$$k = \frac{n d^4 \pi}{128 \mu l}$$

- conduit number
- conduit diameter
- viscosity
- length
An increased hydraulic conductance capacity and higher water transport rates support increased growth and larger plants.
Part 5
Stomates control water loss
Plants can control water loss by changing stomatal aperture

\[
E = 1.6 g (e_i - e_a)
\]

\[
A = g (c_a - c_i)
\]

Franks & Farquhar 2010 Plant Phys
Changing stomatal aperture is an active process

![Diagram showing the process of changing stomatal aperture](image)

- Stimulus
- $\text{H}^+$
- $\text{ATP}$
- $\text{ADP}$
- $\text{K}^+$
- $\text{H}_2\text{O}$
K$^+$ transfer between guard (G) and subsidiary (S) cells allow for increased stomatal movement.
Changing stomatal aperture is an active process
Subsidiary cells (S) allow guard cells (G) to overcome the mechanical advantage.
Stomata respond to a variety of environmental conditions.
Not all graphics and images are original. We acknowledge materials from these sites:
http://www.slideshare.net/eziennker/seed-plants-characteristics
https://c1.staticflickr.com/9/8007/7131296595_1c276b0261_b.jpg
http://www.microscopy-uk.org.uk/micropolitan/botany/schlumbergera_stomata.jpg