Lecture #3
Water
Introduction

Of all the factors that one has managing in a greenhouse or interiorscape, water is the most difficult. It is an art and a science.

Too much, too little, too soon, too late, too cold, too hot, too acidic, too alkaline or too full of certain materials can cause death in tropical plants.

You must understand how water works and is circulated in plants, to manage it properly.
How much water is this tree holding up?

Given how much water weighs, there must be a great amount of weight generated by water in this tree?

How does it get up to the top? There are no pumps in plants! How does it stay in the plant?

If a lower branch breaks, why doesn't water come pouring out?
We use gravity to distribute water to communities. Water towers use strong pumps to slowly bring the water up to a reservoir. The effect of gravity acting on this tank full of water is enhanced by forcing the water to flow down through a small pipe. The result is massive water pressure!

If gravity is such a potent force... why doesn't the water in trees rush out of the roots, or spill out of cut branches?

The answer lies blowing in the wind, within fancy tree anatomy, and in the chemical properties of water.
The first thing to review is the concept of magnetic charges. Many things have positive or negative charges, including magnets and most molecules. “Like” charges repel each other as is seen in the first video clip below. “Opposite” magnetic charges are attracted to each other, as is demonstrated in the second video clip. Lucky for us, water molecules work in the same way!
Cohesion Of Molecules

Water molecules have a charge!

\[ +H \quad \text{and} \quad +H \quad \text{and} \quad O^- = +H_2O^- \]

Opposite charges attract, and therefore water molecules easily become a chain!

\[ +H_2O^- +H_2O^- +H_2O^- +H_2O^- \]

If the molecular bond is strong enough, and you can pull one molecule with enough force, the rest of the water chain will follow. **This is called cohesion!** However, you must never break the chain! Too much force and you can cause a break in the chain.
Adhesion Forces

Charges on the molecules of plastic in the straw are sufficient to pull the water to the sides of the straw. This force is greater than the force of gravity on that volume of water. The smaller the straw, the more the side charges overcome gravity. Phloem and xylem are very, very small tubes, and have a very strong attractive force compared to relatively small gravity force exerted on the very small volume of water.

Note the raised “meniscus”
Adhesion/Cohesion Principle

From which came the “quicker-picker-upper!”?
Fibers of xylem quality in paper towels are actually very, very tiny tubes!

The tubes of xylem are intact and interlaced. If sheets are orientated up and down, the solution will appear to defy gravity. The liquid will move internally and externally, fiber to fiber via the forces of Adhesion and Cohesion, along the water gradient, until the entire volume of water weighs more than the holding force of the fibers and the gradient. Then flow stops.
The Down Fall of Adhesion / Cohesion!

In drought, or when stems are cut, or when cuttings are taken, the chain of water is broken. There is no longer a passive supply of new water molecules. The chain of water continues until it evaporates from the leaves. The remaining water below the break stops and may slowly return back to the roots.

When the water chain is broken, wilting and death of the plant part cut off from the flow is almost inevitable!
Cavitation

In trees, when the chain of water is broken in a xylem vessel, it makes a discernable “pop”. This event is called cavitation.

During extreme drought, sensors can pick up repetitive cavitation in trees….it can sound like a small machine gun!

Embolism
Now we know how water is held up in trees. We have yet to determine how water is pulled up trees, despite the tremendous force of gravity. As there are no pumps, what could possibly provided enough energy to pull the chains of water molecules up?

The answer is not in this picture!
The answer is in this one!

The force that pulls water to the top of the plant is sun and wind driven evaporation from the leaves!
Temperature affects molecular bonds. The warmer the molecule, the faster it moves around.

If enough heat is applied, the energy causes the cohesion bonds of water to break.

Plant leaves can become very warm when bright light from the sun bombards them.

This can generate very active water molecules and increase the number that can break free of the chain and become vapor. These molecules can then escape to the outside through the numerous stomata in the leaf! Therefore sunlight enhances evaporation!
Leaf Anatomy Is Very Important!
A cross section of leaves clearly shows the air spaces in the spongy parenchyma cells.

FIGURE 10.3. Anatomical features of leaves grown in different light environments. These are scanning electron micrographs of (a) a leaf grown in sunlight and (b) a leaf from the same tree but grown in the shaded environment within the canopy. The palisade (column-like) cells are much longer in leaves grown in sunlight. Layers of spongy parenchyma cells can be seen below the palisade cells. Bar = 10 μm. (From McCain et al., 1988.)
Factor 2: Gas Exchange & Wind!

The spongy parenchyma cells are very special. These air spaces allow for gas exchange in addition to providing a membrane surface for water evaporation. Gasses such as $CO_2$ and $O_2$ are freely exchanged. In many ways, this area of plant tissue acts very much like our lungs.

For best results, plants need to be kept relatively stress free so that stomates stay open and allow gasses to exchange freely. A drought-stricken plant is not likely to have optimal gas exchange.
The air outside the leaf is much dryer than the air between the parenchyma cells. The greater the difference in humidity levels, the faster evaporation can occur.

Transpiration is the term we use to describe the heat-driven, humidity gradient-enhanced, mechanism for water evaporation from plant leaves.
Diffusion

Substances flow from an area of high concentration, to an area of low concentration.

Temperature can affect the speed of the process, as can differences in density or concentration.
### Number of Stomata Per Square Inch of Leaf

<table>
<thead>
<tr>
<th>Plant</th>
<th>Upper Epidermis</th>
<th>Lower Epidermis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apple</td>
<td>0</td>
<td>250,000</td>
</tr>
<tr>
<td>Bean</td>
<td>26,000</td>
<td>160,000</td>
</tr>
<tr>
<td>Corn</td>
<td>39,000</td>
<td>64,000</td>
</tr>
<tr>
<td>Black Oak</td>
<td>0</td>
<td>375,000</td>
</tr>
<tr>
<td>Orange</td>
<td>0</td>
<td>290,000</td>
</tr>
<tr>
<td>Pumpkin</td>
<td>18,000</td>
<td>175,000</td>
</tr>
<tr>
<td>Sunflower</td>
<td>55,000</td>
<td>100,000</td>
</tr>
</tbody>
</table>
## Mid-Summer Water Loss per Day

<table>
<thead>
<tr>
<th>Plant</th>
<th>Water Loss (in quarts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A single corn plant</td>
<td>3-4</td>
</tr>
<tr>
<td>A single giant ragweed plant</td>
<td>6-7</td>
</tr>
<tr>
<td>A single young 10-ft apple tree</td>
<td>10-20</td>
</tr>
<tr>
<td>A 12-foot columnar cactus</td>
<td>0.02</td>
</tr>
<tr>
<td>A coconut palm in moist tropics</td>
<td>70-80</td>
</tr>
<tr>
<td>A date palm living near an oasis</td>
<td>400-500</td>
</tr>
</tbody>
</table>
## Water Losses from Single Plants During A Growing Season

<table>
<thead>
<tr>
<th>Plant</th>
<th>Days</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>Corn</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>Sunflower</td>
<td>90</td>
<td>125</td>
</tr>
<tr>
<td>Ragweed</td>
<td>90</td>
<td>140</td>
</tr>
<tr>
<td>Apple tree</td>
<td>188</td>
<td>1,800</td>
</tr>
<tr>
<td>Coconut</td>
<td>365</td>
<td>4,200</td>
</tr>
<tr>
<td>Date Palm</td>
<td>365</td>
<td>35,000</td>
</tr>
</tbody>
</table>
The Pump!

Water is pulled upward by vapor pressure deficit established by the transpiration of water from the open leaf stomates.
Light and Heat Drive The Process!

light strikes leaf 100%
absorbed light 80-85%
transmitted light = 5%
reflected light 10-15%

most of absorbed energy lost in heat and in evaporation of water

only 0.5 to 3.5% of total light energy used in photosynthesis
Relative Humidity

Effect of relative humidity on a plant leaf

Relative Humidity = 10%

Relative Humidity = 50%
Relative Humidity

Effect of relative humidity and air temperature on a plant leaf

Relative Humidity = 50%

90°F

70°F

Relative Humidity = 50%
Stomates Regulate Water Loss

Water potential (water status in cells) regulates opening and closing of the stomates.

Presence or absence of light also regulates the stomates. Thus drought can impair leaf gas exchange and limit photosynthate production.
Many tropical plants require numerous stomates to allow sufficient water to be drawn out of the leaves under high humidity.

Cacti and many dry-subtropical plants have few stomates to conserve water.

What happens if a tropical plant is grown in a dry, warm office environment?

What if a cactus is grown in a fairly dark, humid atrium environment?
Air Movement Drives Nutrient Uptake!

Air movement across the leaf surface strips away water molecules that have emerged from the stomates, intensifying the water loss gradient and speeding up whole-plant water loss.

As more water is released, more nutrients from the soil solution are drawn up with the water entering the roots.

Therefore, air movement does more than just keep water moving, it aids in nutrient uptake and distribution in the plant.
So what happens when a plant is put in a small, cool, dark interiorscape with very little air movement ... and the plant is fertilized weekly?

What happens when a plant is put in a very warm interiorscape with low humidity, high air movement and bright sunlight ... and fertilized weekly?

You lose money!
Wilting

An early warning sign that there is not sufficient water in the plant vascular system is “Wilting.”

Water pressure in the cells aids the structural strength and integrity of the plant. If evaporation is greater than root absorption, or drought prevents replenishment, the water “pressure” drops, causing cells to become flaccid, causing stems and leaves to droop.

This is a temporary problem.
Wilting and Future Growth

Maintaining water turgor (pressure) in a plant is important.

The drop in pressure causes stomates to close, reducing water loss. The plant may be OK but the long term effects on growth can be very serious and take time to show up.

What effects can you think of?
The Permanent Wilting Point

There is also a point in the process of wilting when the plant cell structure, which uses water to aid in cell rigidity, finally collapses irreversibly.

This point of no return is called the “permanent wilting point” or PWP.

You may add all the water you like to the plant system, but the cells will not recover, and the plant will stay wilted, and likely die.
We need to provide cuttings a film of water over their leaves to reduce evaporation, and the loss of water from the stems. Remember, there are no roots to replace the water! It must be adsorbed by the stem cut surface and the leaves, and this is very inefficient!
Root Anatomy

There are several distinct growth zones on a healthy 2" root. The tip of the root is primarily undifferentiated cells. The next 1/3 are cells that are elongating and are differentiating. The upper 1/3 are mature cells with developing root hairs.

Farther up the root, the root hairs die and the epidermis becomes less permeable. Therefore, only the last inch of a growing root is involved in uptake.
Root hairs work by the cell nucleus forming an extension of the cell membrane, this forming the root hair.

There is only one nucleus, if the membrane appendage is damaged, the nucleus is usually killed and no new hair can be formed. The epidermal cell usually dies.
Over Watering

Roots need oxygen and water!

Roots are a membrane interface to the outside environment. Like the leaves, gas exchange does take place in the roots. In this case, roots need oxygen to respire, and give off CO2.

If you provide water too often, the air spaces with the soil stay filled with water, and do not allow gasses to flow through the soil. The plant roots actually suffocate. Proper watering flushes old air out and draws in new air. Can you determine why?

Roots will not grow into oxygen-depleted soil.
Over-Fertilization

Adding fertility in excess of the rate it is use by the plant causes build up, especially in containers with no weep holes.

Excess fertilizer can cause big problems for roots, and can actually cause nutrient toxicity and deficiency.

Fertility levels must be checked regularly, and soils flushed out at least twice a year. That, or pay good money for a repotting!
When fertilizer-laden soils dry out, the salts concentrate and literally form crusts. To stay stable, salts need to bind with water. This water binds very tightly. If many salt crystals form, and water is scarce, the salt formation process will actually cause a reverse gradient and pull water out of the outer root cells, dessicating and killing them. This is called salt burn,

Note salts below the water evaporation zone!
The Economics Of Root Formation

Regardless of whether you have a cutting or a salt damaged plant, new roots are what you need, fast!

Constant humidity, and plenty of air spaces in the soil will encourage new root hairs to form, and new meristem tissue to develop new root initials. You must concurrently reduce stress, control temperature, maintain or improve light and yet maintain low fertility and low water loss from leaves.

This takes time, patience, consistent care and $$$!
New Installations Are Like Cuttings!

Providing water to plants in a new installations is a tricky business. Watering must be only when needed, and never too late. Mulch, such as Tillandsia (spanish moss), or bark chips can be added to reduce direct evaporation from soil. Plants can also be moved into less direct light to reduce evaporation until roots re-grow and the plants settle in.

Frequent site visitation is essential!
Overview Of Water Transport System In Plants

Each Plant Is Different

Know Your Plants!

The driving force: evaporation:
1. Evaporation from cell walls, due to much lower water potential of air.
2. Creates a lower water potential in:
   a. cell walls
   b. celloplasts
3. Energy ultimately came from the sun (warmed air, water).

Cohesion in the xylem:
4. Water columns, under tension, hold together by cohesion.
5. Due to capillary dimensions of the xylem elements.
6. If cavitation occurs, bubble will not pass to another element (check valve).

Water uptake from the soil:
7. Negative water potential is finally transferred to root cells and soil.
8. Root hairs increase absorbing surface.
9. Passage through endodermis may be osmotic.
Trees Are Amazing!