Vegetation, Part 2:
Physical characteristics of vegetation canopies:
Leaves, Stems and Roots

• Leaf Size and Shape
• Leaf angle distribution, inclination and azimuth
• Spatial distribution of leaves
  – projected to surface area ratios
  – shoots and non-flat leaves
  – clumping relations
• Basal area and woody biomass index
• Leaf anatomy
• Specific leaf area
• Canopy height
• Chemical composition of leaves, stems, roots (C/N ratios)
• Rooting depth
• Soil depth and water
Leaf size, shape and orientation affect

- the properties of the **leaf boundary layer**;
- the **reflectance** and **transmittance** of light
- leaf’s **energy balance**
shape and size of leaves

- needles vs planar
- projected vs surface area of needles
- shoot to total needle area
- Big vs Small
Shapes of Planar leaves

- undulate
- sinuate
- serrate
- dentate
- lobate
- scalloped
- palmate
- digitate
- bipinnatisect
- tripinnatisect
- pinnatisect
- palmatisect
- pedate
- palmatilobate
- bipartite
- tripartite
- palmatipartite
- pinnatipartite
- pinnatifid
Conifer Fascicles and Shoots

Pine
Spruce
Fir
Douglas fir
Cedar
larch
Foliage Types on Conifers
Leaf exposure/acclimation

- sunlit/shaded
  - Penumbra
  - Umbra
- Climate
  - Wet
  - Dry
- Thickness
- Density
- Clumping
- Angle
Vertical variation of redwood leaf morphology with height

Koch et al. 2004 Nature
Vertical Attributes of Plants

- **canopy height**
  - Trees
    - Redwoods, ~80m
    - Hardwood forest, ~30 m
  - Shrubs
    - Savanna, ~10m
    - Chaparral, ~3 m
  - Grasses
    - Corn, ~3m
    - Grass, ~0.1 m
  - Herbs
    - Soybeans, ~1m
Measure Canopy Height: Classic Methods

Ruler/ Tape Measure

Hypsometer/Inclinometer

\[ A = \tan \theta_a \times D \]
\[ B = \tan \theta_b \times D \]
Tree height = A + B

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Seasonal variation of canopy height of a soybean canopy

Clark soybeans
1979, Mead, NE

D. Baldocchi, Ph.D. dissertation
Ultra sonic Snow depth sensor
Measure Canopy Height: New Methods

Airborne LIDAR

Ground Based LIDAR
Transect of tree height at the Wind River Crane Field site: an old growth Douglas fir forest.

Vertical scale of elevation reduce by 10x

Ground surface

Lefsky et al 2001 Bioscience
Airborn Lidar: Oak Savanna, Ione, CA

Baldocchi et al 2010
Take a Virtual Ride through a Sequoia Tree

https://www.youtube.com/watch?v=oCXNofFDe5Q
Map of Tree Height

Figure 1. Global forest height map. Heights are the 90th percentile of GLAS height observations within a patch.
Leaf Angles and Light Interception

Cereal Grains have been Bred to Optimize Light Interception by Establishing Canopies with Erect Leaves
leaf angle distribution

- Erectophile
- Planophile
- Spherical
- Azimuthally symmetric or asymmetric
Leaf inclination angle distribution for three leaf angle classes

Leaf angle distribution functions

- planophile
- erectophile
- extremophile

f(α)

leaf angle
Cumulative leaf angle distribution

\[ \int_{0}^{\pi/2} g(\theta_L) \, d\theta_L = 1 \]
Leaves are Horizontal in the understory of a temperate forest

Beech Forest, Hainich, Germany
Leaf Angles Vary with Depth in a Forest

![Graph showing cumulative area-weighted frequency distributions of the inclination angles of leaves in the three major strata of a deciduous forest in eastern Tennessee, U.S.A.]

**Fig. 3.** Cumulative area-weighted frequency distributions of the inclination angles of leaves in the three major strata of a deciduous forest in eastern Tennessee, U.S.A.

Hutchison et al., 1986, J Ecol
Leaves are Erect in a Sunny, Open, Blue Oak Woodland in CA

Level 1: 0 - 2 m (total 201 samples)

Mean: 57.5
STD: 24

Data of Youngryel Ryu, Rodrigo Vargas, Oliver Sonnentag

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Measure Leaf Angles: Class Project

Take Digital Picture with Cell Phone

Upload image to ImageJ software
http://imagej.nih.gov/ij/

Scan leaves and record angle

Compute Histogram

Submit and Share on Class Database, Google Doc
Frequency distributions of leaf angle for 16 of 38 study species from the two study sites in Australia.

**steep leaf angles** to reduce exposure to **excess light** than to maximize solar interception to maximize carbon gain

Falster and Westoby 2003
Annual sums of net CO$_2$ exchange as a function of leaf inclination angles and clumping

<table>
<thead>
<tr>
<th></th>
<th>clumped</th>
<th>random</th>
<th>spherical</th>
<th>erectophile</th>
<th>planophile</th>
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<tbody>
<tr>
<td>NEE (gCm$^{-2}$ a$^{-1}$)</td>
<td>-577</td>
<td>-354</td>
<td>-720</td>
<td>-1126</td>
<td>-224</td>
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</table>

- We assumed the mean angle for the erect canopy was 80 degrees and it was 10 degrees for the plane canopy.
- The mean direction cosine between the sun and the leaf normal is 0.5 for the spherical case.
Spatial attributes of Plant Canopies

• crown volume and shape
• plant species
• stem density
• spatial distribution of plants
Horizontal (spatial) distribution

• **Leaves**
  – Random dispersion
  – Clumped dispersion
  – Regular dispersion

• **Plants**
  – Random
  – Rows
  – Clumped
Spatial distribution of plants

- Regular
- Clumped
- Quasi-regular
- Random
Hierarchy of Canopy Abstractions for Canopy Radiative Transfer Models

Reality

3-D Representation

2-D Representation

1-D Representation

Niwot Ridge Flux Course 2014
Physiological Attributes of Plants

- photosynthetic pathway
  - $C_3$
  - $C_4$
  - CAM
Physical Attributes of Roots

- **rooting** depth
- root architecture
  - Fibrous
  - Tap
Sampling Roots

Holes and Shovel  Ground Penetrating Radar  Hydraulic Excavation

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Measure Roots with Ground Penetrating Radar

Raz-Yaseef et al. 2013 JGR Biogeoscience
Sub Sampling Fine Roots

1. **Core Sample**
   - In-tact soil core containing soil and roots

2. **Sieving**
   - 1 mm mesh
   - Soil and rocks and large debris are removed and discarded.
   - Roots > 1 cm length removed and set aside for drying and weighing.
   - Residual Fraction = all remaining roots and debris captured by the sieves.

3. **Sub-sampling**
   - 0.25 mm mesh
   - Roots and debris are randomized through mixing and sub-sampled.

4. **Sub-samples x 10**
   - Sorted into paired samples of roots and debris

5. **Equipment for sub-sampling**
   - Syringe, stir bar, “plunger”, mixing plate

Koteen Baldocchi, 2013 Plant Soil
Root Distribution

Cumulative Distribution

Depth

0.0 0.2 0.4 0.6 0.8 1.0 1.2

B = 0.98
0.90
Model parameters on cumulative root distribution \((Y=1-B^z)\)

<table>
<thead>
<tr>
<th>Biome</th>
<th>B, total roots</th>
<th>% roots in upper 30 cm</th>
<th>B, fine roots</th>
<th>% roots in upper 30 cm</th>
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</thead>
<tbody>
<tr>
<td>boreal forest</td>
<td>0.943</td>
<td>83</td>
<td>0.943</td>
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<td>desert</td>
<td>0.975</td>
<td>53</td>
<td>0.97</td>
<td>60</td>
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<td>sclerophyllous shrubs</td>
<td>0.964</td>
<td>67</td>
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<td>temperate conifer forest</td>
<td>0.976</td>
<td>52</td>
<td>0.98</td>
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<tr>
<td>temperate deciduous forest</td>
<td>0.966</td>
<td>65</td>
<td>0.967</td>
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<td>0.943</td>
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<td>tropical deciduous forest</td>
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<td>tropical savanna</td>
<td>0.972</td>
<td>57</td>
<td>0.972</td>
<td>57</td>
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<tr>
<td>tundra</td>
<td>0.914</td>
<td>93</td>
<td>0.909</td>
<td>94</td>
</tr>
</tbody>
</table>

After Jackson (1999)
Root-Weighted Soil Moisture

\[ <\theta> = \frac{\int_{0}^{z} \theta(z) p(z)\,dz}{\int_{0}^{z} p(z)\,dz} \]

Cumulative probability, \( Y = 1 - B^z \)

Probability density, \( P = dY/dz \)
Summary

• Structural and functional properties of plant canopies alter:
  – wind and turbulence within and above the canopy, by exerting drag;
  – the interception and scattering of photons throughout the canopy;
  – the heat load on leaves and the soil;
  – the physiological resistances to water and CO2 transfer
  – the biochemical capacity to consume or respire carbon dioxide.
Summary

• Plant height
  – the aerodynamic roughness of the canopy
  – the ability to transfer water from the roots to the leaves
  – alters the ability of a canopy to trap light
  – laser altimeters give us a new way to visualize and quantify the height and its variability in tall forests.
  – Tree height is limited by a combination of physical limits to transfer water to great heights and the metabolic costs of support biomass to do this.

• Leaf Inclination Angles
  – Leaf angles of plants vary due to natural selection, light acclimation and genetic breeding
  – Leaves deep in the canopy tend to be horizontal, while those near the top are more erect
  – Leaf inclination angles affect light transmission through plant canopies and and net primary productivity

• Leaf Anatomy
  – Leaf anatomy is a function of photosynthetic pathway (functional type) and acclimation
  – Leaves near the top of the canopy are thicker where they tend to be sunlit than those near the bottom, which tend to be shaded
  – There are physical limits to leaf thickness imposed by limits to diffusion and light attenuation

• Roots
  – Root density decreases with a power law function of depth
  – Use Root models to compute Root Weighted Soil moisture
Take Home Points

• Physical attributes of a canopy include
  – leaf area index
  – canopy height
  – leaf size.

• Physiological attributes of a canopy include
  – photosynthetic pathway
  – stomatal distribution (amphi or hypostomatous)

• The physical and physiological attributes of a canopy can vary
  – in space (vertically and horizontally)
  – in time (seasonally and decadally).
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Structural or Functional Attribute</th>
<th>Primary Impacts on Carbon, Water and Energy Fluxes</th>
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</thead>
<tbody>
<tr>
<td>Leaves</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Photosynthetic pathway</td>
<td>C₃, C₄, CAM, maximal stomatal conductance</td>
<td>Cᵢ, Gₛ</td>
</tr>
<tr>
<td>Leaf size/shape</td>
<td>Needle/planar/ shoot; projected/surface area, penumbra/umbra</td>
<td>Gₛ, P(0)</td>
</tr>
<tr>
<td>Leaf inclination angle</td>
<td>Spherical, erectophile, planophile</td>
<td>P(0)</td>
</tr>
<tr>
<td>distribution</td>
<td></td>
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<tr>
<td>Leaf azimuthal angle</td>
<td>Symmetric/asymmetric</td>
<td>P(0)</td>
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<td>distribution</td>
<td></td>
<td></td>
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<tr>
<td>Exposure</td>
<td>Sunlit/shaded; acclimation</td>
<td>Cᵢ, Gₛ, α</td>
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<tr>
<td>Optical properties</td>
<td>Reflectance, transmittance, emittance</td>
<td>α</td>
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<tr>
<td>Leaf thickness</td>
<td>Photosynthetic capacity, supply of CO₂ to chloroplast, optical properties, Stomatal conductance capacity</td>
<td>Cᵢ, Gₛ, α</td>
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<tr>
<td>Stomatal distribution</td>
<td>Amphistomatous/hypostomatous</td>
<td>Gₛ</td>
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<tr>
<td>Plants/Trees</td>
<td>Cone, ellipse, cylinder</td>
<td>P(0), G_a</td>
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<tr>
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<tr>
<td>Crown volume shape</td>
<td></td>
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<tr>
<td>Plant species</td>
<td>monoculture, mixed</td>
<td>P(0), G_a, G_s, C_i</td>
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<tr>
<td>stand, functional type</td>
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<tr>
<td>Spatial distribution of leaves</td>
<td>Random, clumped,</td>
<td>P(0)</td>
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<tr>
<td>leaves</td>
<td>regular</td>
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<tr>
<td>Plant habit</td>
<td>Evergreen/deciduous;</td>
<td>G_a, G_s, (\alpha)</td>
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<td>woody herbaceous; annual/perennial</td>
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<td></td>
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<tr>
<td>Plant height</td>
<td>Short (&lt; 0.10 m)</td>
<td>G_a, (\alpha)</td>
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<tr>
<td>tall (&gt; 10 m)</td>
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<td>Rooting depth</td>
<td>Accessible water and</td>
<td>G_s</td>
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<tr>
<td>nutrients, plant water relations</td>
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<tr>
<td>Leaf area/sapwood ratio</td>
<td>Hydraulic Conductivity</td>
<td>G_s, C_i</td>
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<td>Forest Stand</td>
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<td>------------------------</td>
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<tr>
<td>Leaf area index</td>
<td>Open, sparse, closed</td>
<td>P(0), G_s, G_a</td>
</tr>
<tr>
<td>Vertical distribution of LAI</td>
<td>Uniform, skewed</td>
<td>G_a, P(0)</td>
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<tr>
<td>Seasonal variation of LAI</td>
<td>Evergreen/deciduous; winter or drought deciduous</td>
<td>G_a, G_s</td>
</tr>
<tr>
<td>Age structure</td>
<td>Disturbed/undisturbed; plantation; agriculture; regrowth</td>
<td>G_a, G_s, P(0)</td>
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<tr>
<td>Stem density</td>
<td>Spatial distribution of plants</td>
<td>G_a, α</td>
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<tr>
<td>Woody biomass index</td>
<td>Amount of woody biomass</td>
<td>G_a, P(0)</td>
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<tr>
<td>Topography</td>
<td>Exposure, site history, water balance</td>
<td>G_a, G_s</td>
</tr>
<tr>
<td>Site history</td>
<td>Fires, logging, plowing, re-growth</td>
<td>G_a, G_s, C_p, α</td>
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<tr>
<td>Parameter</td>
<td>grass/cereal</td>
<td>shrub</td>
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<tr>
<td>---------------------------------</td>
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<tr>
<td>LAI</td>
<td>0-5</td>
<td>1-7</td>
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<tr>
<td>fraction of ground cover</td>
<td>1.0</td>
<td>0.2-0.6</td>
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<td>understory LAI</td>
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<td>leaf normal orientation</td>
<td>erectophile</td>
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<tr>
<td>fraction of stems</td>
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<tr>
<td>leaf size (m)</td>
<td>0.05</td>
<td>0.05</td>
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<td>crown size</td>
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<table>
<thead>
<tr>
<th>biome</th>
<th>albedo</th>
<th>Height (m)</th>
<th>Zo(m)</th>
<th>LAI max</th>
<th>Rooting Depth</th>
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<tr>
<td>Tropical forests</td>
<td>0.12-0.14</td>
<td>30-50</td>
<td>2-2.2</td>
<td>4-7.5</td>
<td>1-8</td>
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<tr>
<td>Temperate forests</td>
<td>0.1-0.18</td>
<td>15-50</td>
<td>1-3</td>
<td>3-15</td>
<td>0.5-3</td>
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<td>Boreal forests</td>
<td>0.1-0.3</td>
<td>2-20</td>
<td>1-3</td>
<td>1-6</td>
<td>0.5-1</td>
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<td>Arctic tundra</td>
<td>0.2-0.8</td>
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<td>&lt; 0.05</td>
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<td>0.4-0.8</td>
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<td>Mediterranean shrubland</td>
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<td>0.03-0.5</td>
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<tr>
<td>Crops</td>
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<td>variable</td>
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<td>Tropical savanna</td>
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<td>Max $g_s$</td>
<td>$g_a$</td>
<td>Max CO$_2$ flux, day</td>
<td>Max CO$_2$ flux, night</td>
<td>RUE</td>
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<td>------------------------</td>
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<tr>
<td>Units</td>
<td>mol m$^{-2}$ s$^{-1}$</td>
<td>mol m$^{-2}$ s$^{-1}$</td>
<td>$\mu$mol m$^{-2}$ s$^{-1}$</td>
<td>$\mu$mol m$^{-2}$ s$^{-1}$</td>
<td>G(DM)/MJ (PAR)</td>
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<td>0.5-1</td>
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<td>Boreal forests</td>
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<td>10</td>
<td>-12</td>
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<td>Arctic tundra</td>
<td></td>
<td></td>
<td>-0.5 to -2</td>
<td>1-2</td>
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<tr>
<td>Mediterranean shrubland</td>
<td>0.5-1</td>
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<td>-12 to -15</td>
<td>6-7</td>
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<td>Crops</td>
<td>1.2</td>
<td>1-3</td>
<td>-40</td>
<td>2-8</td>
<td>1-1.5</td>
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<td>Tropical savanna</td>
<td>0.2-1</td>
<td>0.1-4</td>
<td>-4 to -25</td>
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<td>0.4-1.8</td>
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<tr>
<td>Temperate grassland</td>
<td>0.4-1</td>
<td>0.2-1.5</td>
<td>-13 to -20</td>
<td>0.5-4</td>
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</tbody>
</table>

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What Limits the Height of Trees?

- **Respiration Hypothesis**
  - Larger Organisms respire more, so they grow less
  - Classic textbook explanation
  - But respiration declines with decline in growth
- **Nutrient Limitation Hypothesis**
  - Sequestration of nutrients in Biomass limits growth
- **Maturation Hypothesis**
  - Older organisms have reduced activity
  - Grafting studies refute it
- **Hydraulic Limitation Hypothesis**
  - Water potential decreases with increasing plant height, leading to restrictions in stomatal opening and photosynthesis
  - Supported by many studies, but not all
- **Wind Load**
  - Tall plants vulnerable to wind throw
Reasons and Limits to Plant Height

• Pros
  – Out-Compete Neighbors for Light

• Cons
  – More Respiration
  – Vulnerability to Wind Throw
  – More Work/Energy needed to move water from soil to leaf
  – Need investment in woody structure to support height