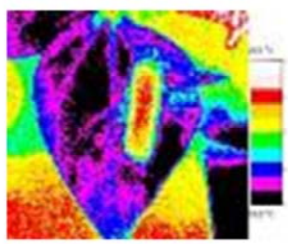
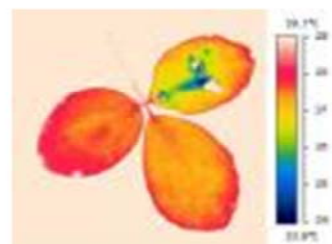
Vegetation, Part 2:
Physical characteristics of vegetation canopies:
Leaves, Stems and Roots

- 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**





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The size of a leaf affects how the boundary layer grows as wind blows across it. This will affect the transfer of heat and mass and will yield gradients in leaf temperature, that can be viewed here with infrared scanners.

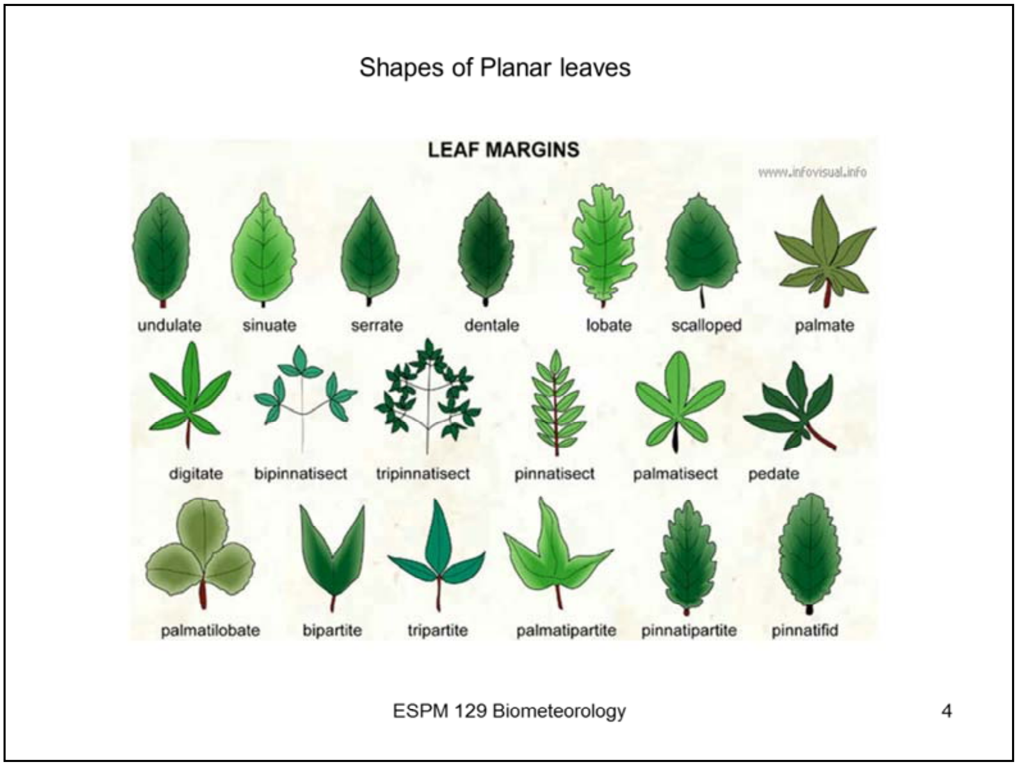
# **shape** and **size** of leaves

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

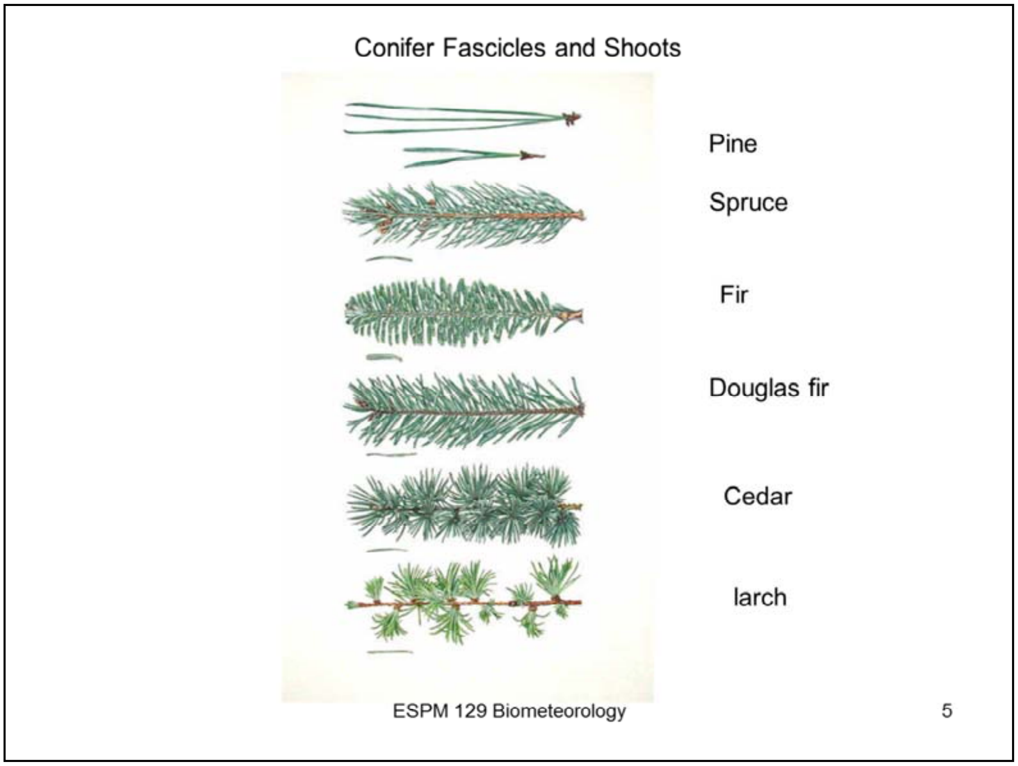





The shape and size of leaves is multi-facted.




There are broad categories of planar leaves with and without lobes, serrated, ovate, multi-leafed




Conifer needles are tiny compared to planar leaves. They have different abilities to shed snow, convect heat and intercept, trap and reflect light

Needle-leaved conifers: 2- and 3-needle pines, spruce, fir, Douglas fir, cedar, larch.

http://www.microscopy-uk.org.uk/mag/imgnov05/drawingandpaintingplants144.1.jpg

## Foliage Types on Conifers




http://www.ext.colostate.edu/mg/gardennotes/images/134-9.jpg

## Leaf exposure/acclimation

- sunlit/shaded
  - Penumbra
  - Umbra
- Climate
  - Wet
  - Dry
- Thickness
- Density
- Clumping
- Angle

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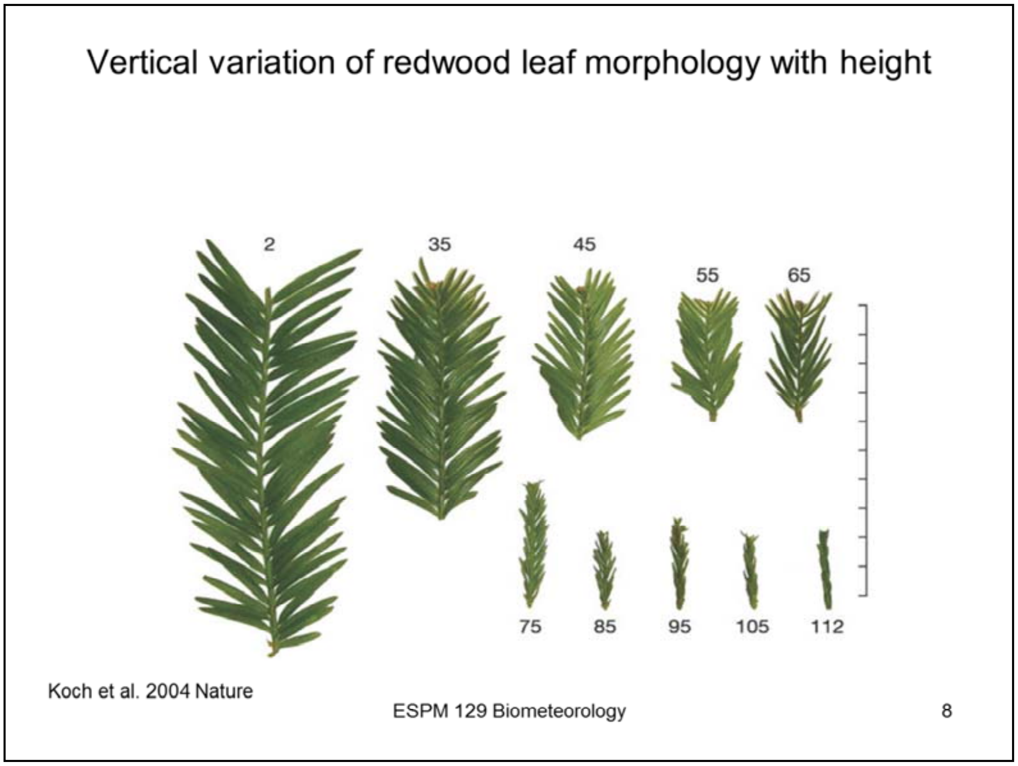
Leaf shape and size, orientation, clumping are all affected by the exposure of leaves to light. Leaves deep in a forest canopy can differ marked from the morphology of those in the upper reaches.




Amazing visual of how a redwood shoot varies with height through the crown. Those in the upper reaches are tiny and look more like junipers. Remember water must be lifted, so gravitational pull imposed a negative water potential on those leaves, exposing them to physiological stress and the upper limits to which leaves can sustain them selves.

# 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**

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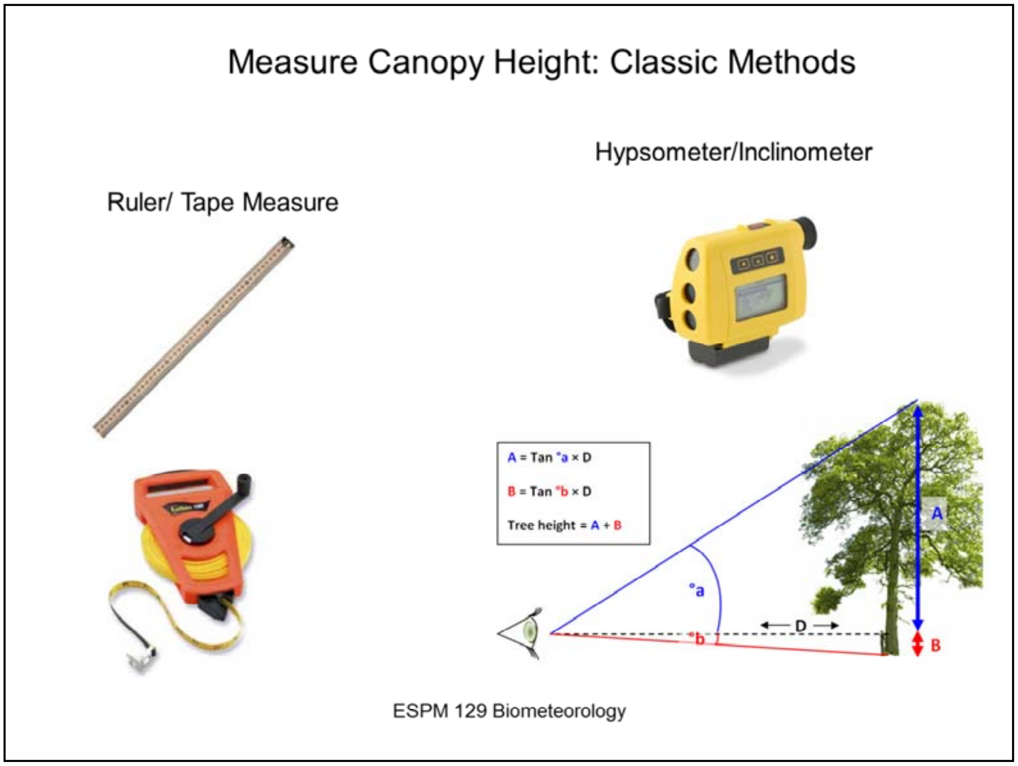
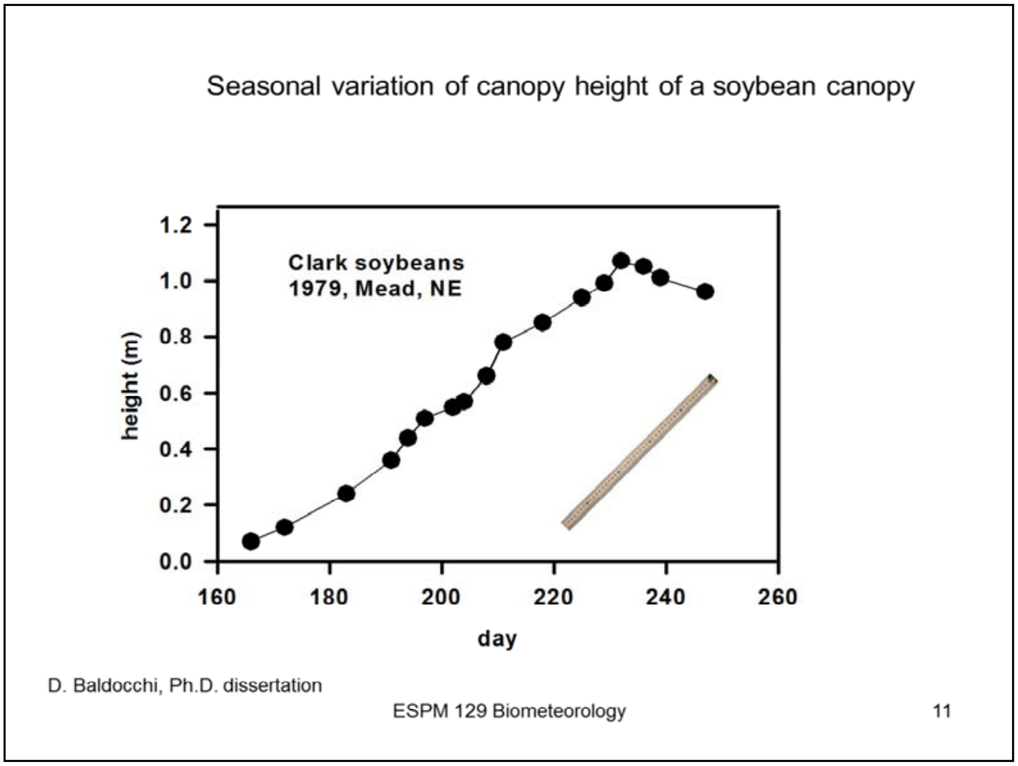
Plant heights tend to span 5 orders of magnitude (0.01 m, 0.1, 1, 10, 100m). Shorter are herbaceous grasses and dicots. Taller are multi-stemmed shrubs and the tallest are single stemmed trees.




How do we measure canopy height? The simplest is with a ruler or tape measure. This works well for grass, crops, alfalfa. For taller trees foresters use a hypsometer or inclinometer and infer height by the angle to the tree top and the distance from the tree and the observer.




Crops grow fast so it is important to measure their height regularly during the growing season. Here are data from my dissertation on soybeans. If one is studying a remote system and cant visit the site regularly how else can one measure height on a routine basis?

## Ultra sonic Snow depth sensor

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It may be possible to use an ultra sonic snow depth sensor, or laser range finder carpenters use to measure distances across rooms

## Measure Canopy Height: New Methods

Airborne LIDAR

Ground Based LIDAR

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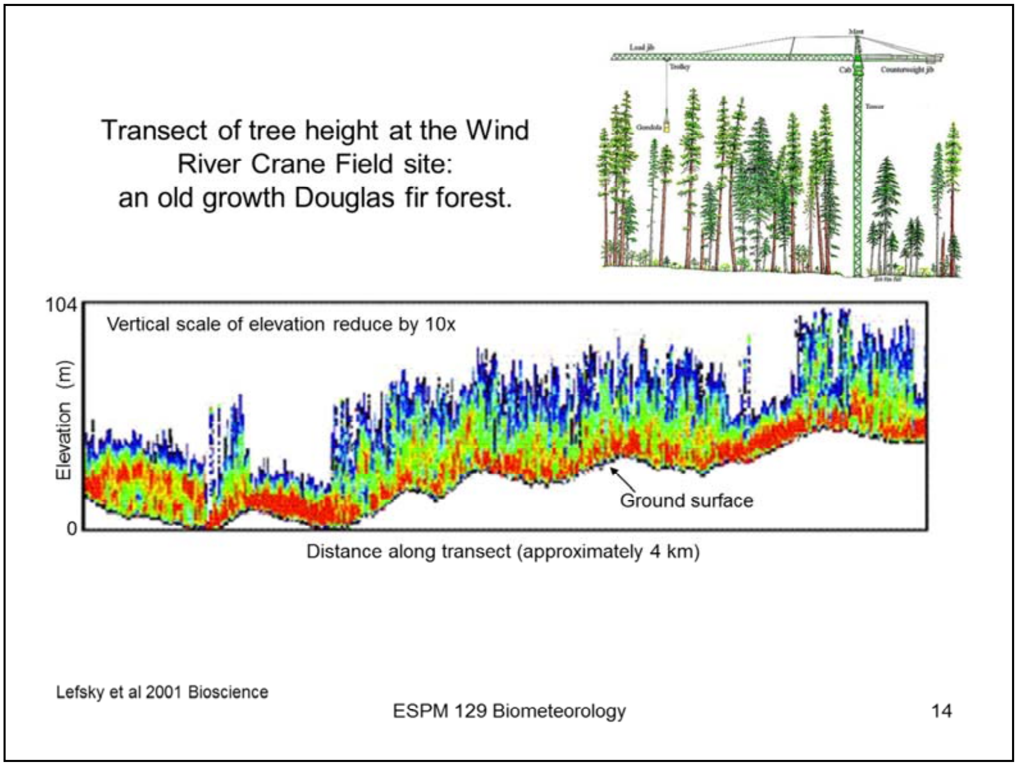
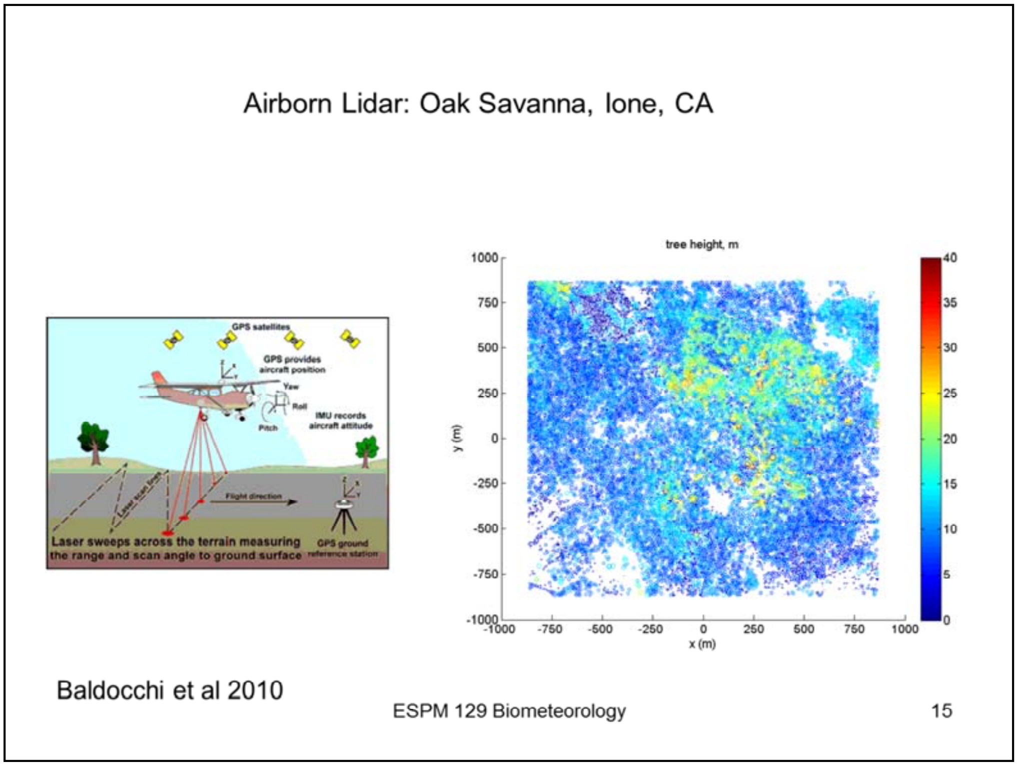
How do we measure canopy height of Taller Forests? New advances with LIDAR are making exquisite measurements of canopy height, size and height of individual trees and through gaps information on elevation and topography. Coarse scale, but broad scale information is being produced with airborne lidar. I have acquired two scenes about 1 km square at my field site. 0.5 m resolution is typical. Finer scale information of individual trees can be produced with ground based lidar. This method is more labor intensive. Both methods produce gobs of data, so data mining, sensor registration, etc, is needed to produce accurate maps.




Here is a published transect of a 90 m tall Douglas fir forest in Washington.  It was served by a crane.




Airborne lidar scene of crown height, tree location and crown size. The difficulty is identifying individual trees when crowns merge or in dense closed canopies

Take a virtual tour through the oak woodland with new terrestrial lidar data from Martin Beland

https://www.youtube.com/watch?v=Si_O0sg6TSU

Take a Virtual Ride through a Sequoia Tree

https://www.youtube.com/watch?v=oCXNofFDe5Q

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My former postdoc, Martin Beland, used a ground based lidar to image a 100 m tall sequoia at Whittaker Forest, in the southern Sierra's. Take a look at the YouTube video and ride up through the canopy. Is the Lidar perfect? Look at the upper reaches of the crown. What do you see, or don't see? Why may this happen?

https://www.youtube.com/watch?v=oCXNofFDe5Q

# Map of Tree Height

L15401 LEFSKY: A GLOBAL FOREST CANOPY HEIGHT MAP L15401

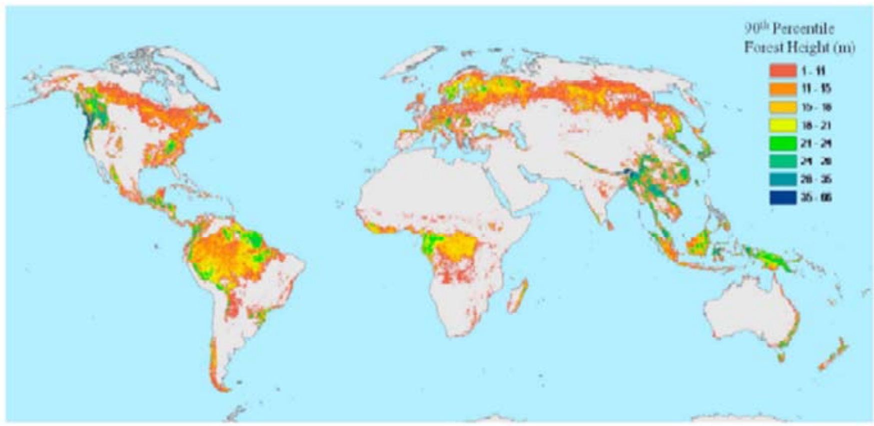


**Figure 1.** Global forest height map. Heights are the 90th percentile of GLAS height observations within a patch.

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The goal is to produce global maps of canopy height with lidar systems on satellites in space. At present there is no dedicated tree lidar. So investigators are using other sensors like those measuring ice at sea or land elevation (GLAS on ICESAT). Sensors like NASA's LVIS has been mounted on planes.

## Leaf Angles and Light Interception

Corn

Rice

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

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Many first time students taking this class have not thought about leaf angles. Yet, how leaves are arrayed on a plant or in a canopy have profound effects on their ability to capture light, when needed, or deflect light capture when there is too much. Lessons on leaf angles are also critical for those interested in solar energy and in designing the optimal solar panel system. If you look closely when you drive though farm country the leaf inclination of high productive monoculture crops tend to be erect, as this enables a closed canopy to capture the most light.

# leaf angle distribution

- Erectophile
- Planophile
- Spherical
- Azimuthally symmetric or asymmetric

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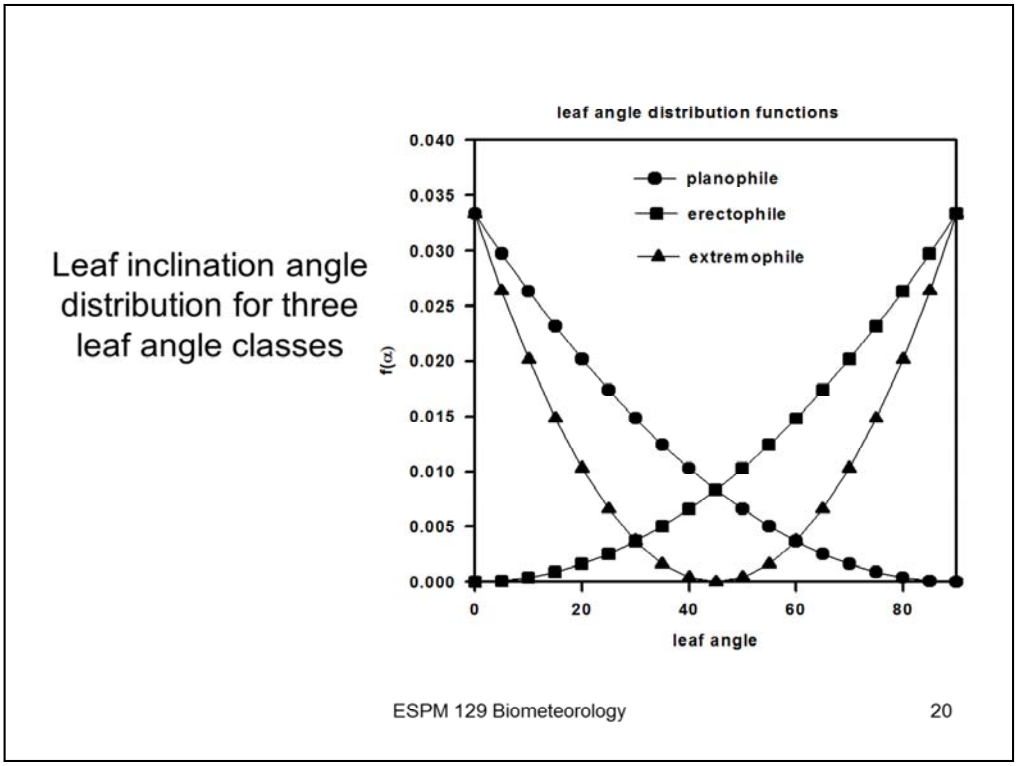
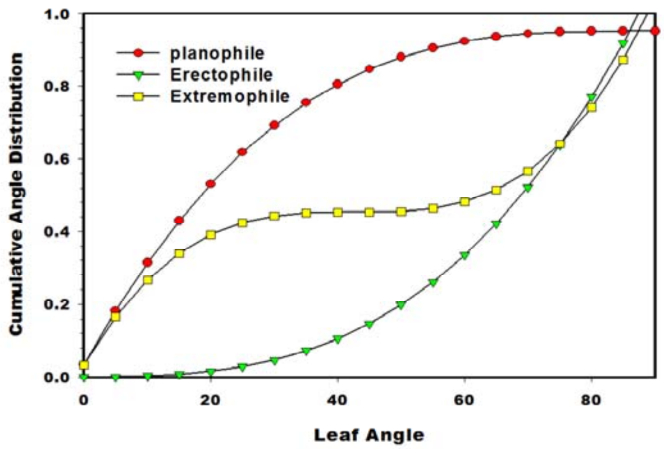
Many leaf angle distributions exist, each with its own specific name.




It is best to understand these different leaf angle distributions by the histogram or probability density function of their leaf angles. Planophile leaves are closest to horizontal. Erectophile have more erect leaves. A spherical distribution has a probability that covers the surface of a ball.

# Cumulative leaf angle distribution

$$\int_0^{\pi/2} g(\theta_L)\, d\theta_L = 1$$

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Remember the sum or integration of leaf angle distributions sum to one. The 50 percentile of the cumulative distribution gives you the median angle.

Leaves are Horizontal in the understory of a temperate forest

Beech Forest, Hainich, Germany

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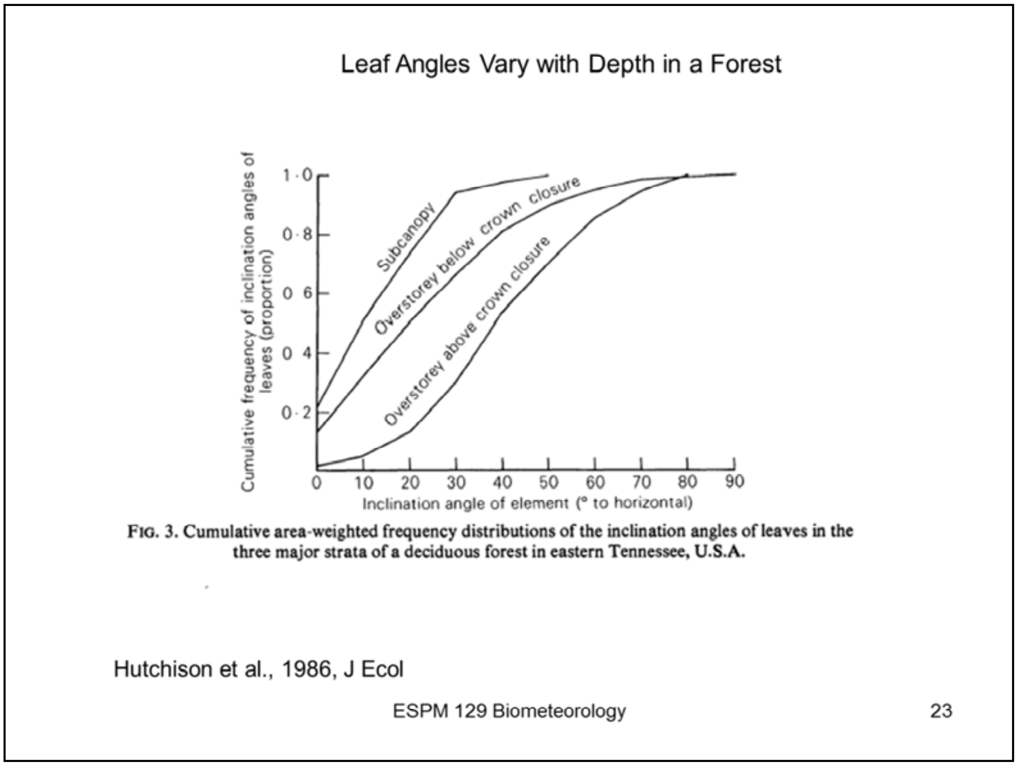
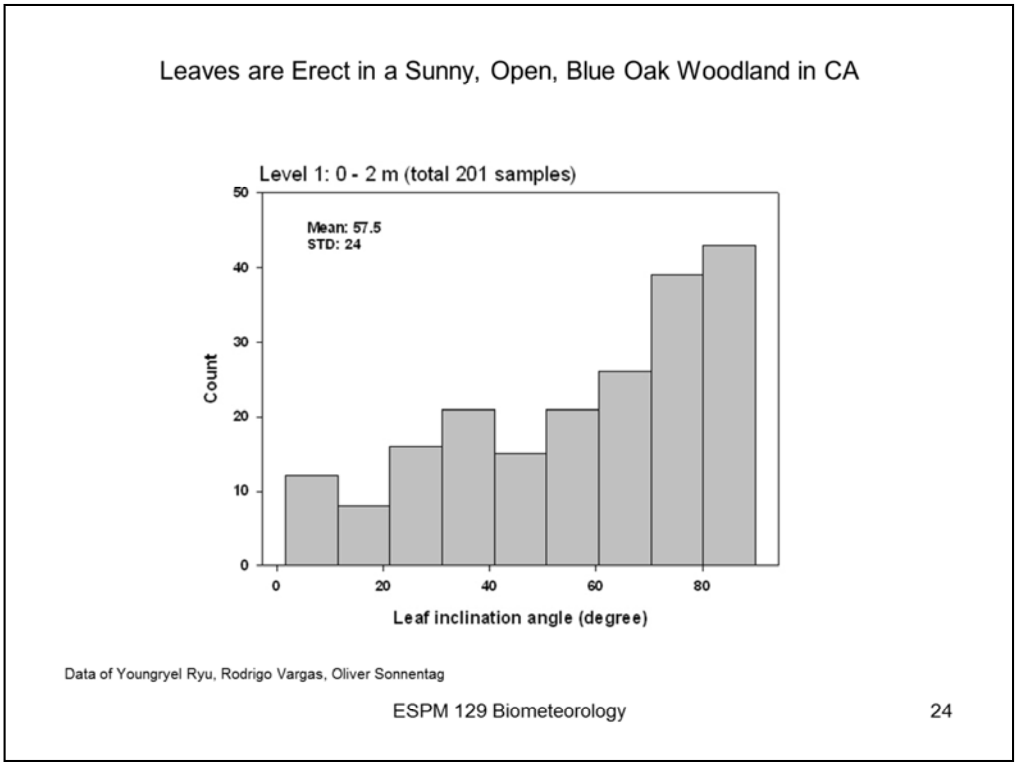
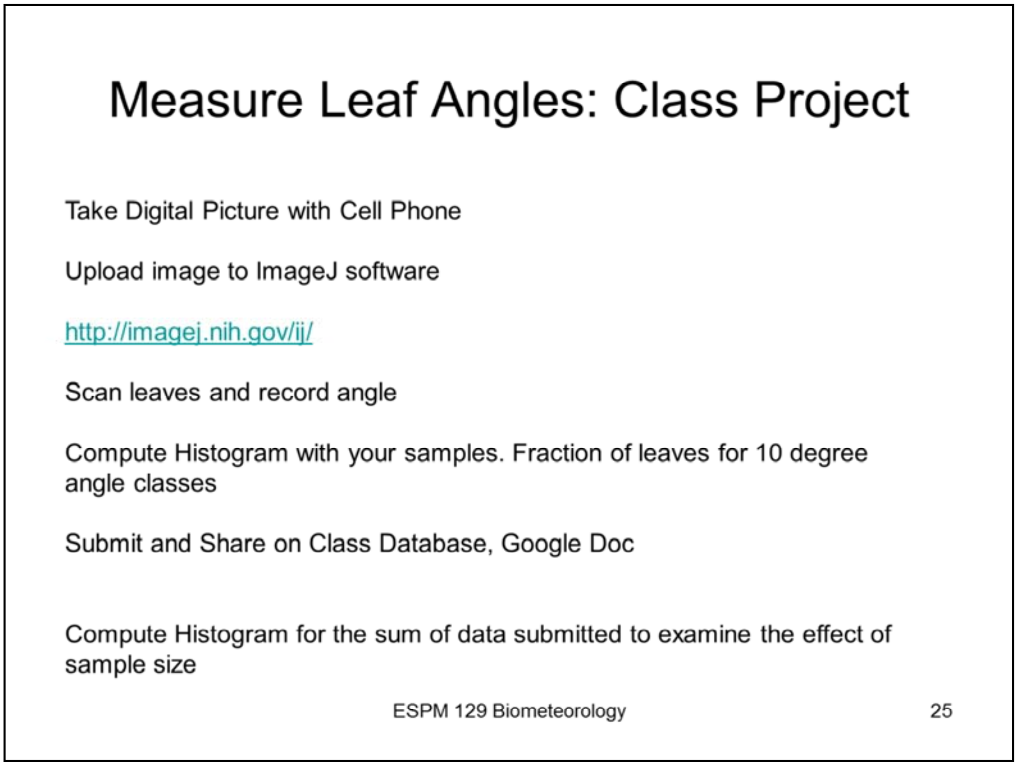
The angle of leaves in a dense forest exhibit much plasticity. If you look closely at the leaves in the understory, many are horizontal, giving them the maximal ability to intercept the diffuse shade photons that dominate this environment.




Work by my former mentor, Boyd Hutchison, revealed how the angles of leaves in the overstory of a forest were much more erect (35 degrees) than those in the understory < 10 degrees)

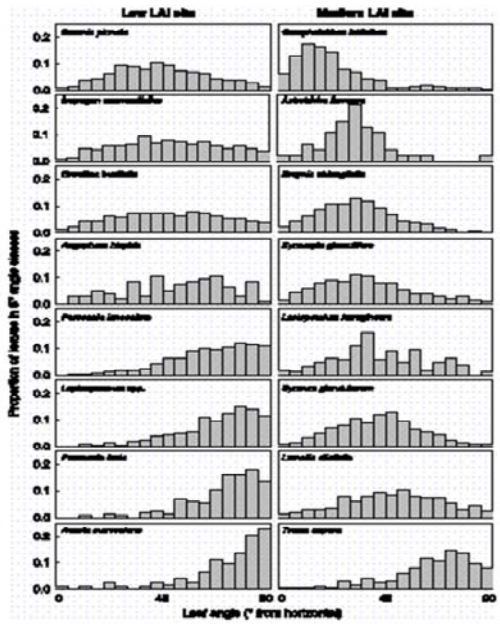



In contrast the angle of leaves of California oak trees, exposed to much more intense light, are more erect (mean 57 degrees)




We will assign an exercise to measure leaf angles and look at sampling errors. More details will be posted on Bcourse.

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



This study across an ecological and climatic gradient in Australia re-enforces the points being made. Most erect leaves in canopies with low leaf area index and full sun exposure

Annual sums of net $CO_2$ exchange as a function of leaf inclination angles and clumping

| | clumped | random | spherical | erectophile | planophile |
|---|---|---|---|---|---|
| NEE ($gCm^{-2}\ a^{-1}$) | -577 | -354 | -720 | -1126 | -224 |

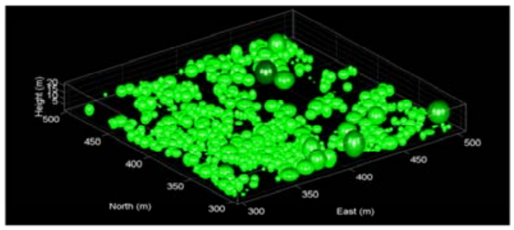
- We assumed the mean angle for the erect canopy was 80 degrees and it was 10 degrees for the plane canopy.
- The mean direction cosine between the sun and the leaf normal is 0.5 for the spherical case.



What is the integrated effect of leaf angle on productivity? We can answer this question using a mechanistic model, like my CANOAK model. Over a year, a forest stand with erect leaves can take up nearly 5 times more carbon than one with flat or planophile leaves.

## Spatial attributes of Plant Canopies

- **crown volume** and **shape**
- **plant species**
- **stem density**
- **spatial distribution** of plants

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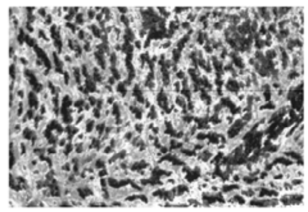
Many of the assumptions of biometeorology is that the vegetation is horizontally homogeneous over an extended distance. While this is a nice assumption, and often works with closed vegetation, it often fails, too. Crops start growing as seeds and only at the end of the vegetative period do they achieve closure. Ecosystems experiencing soil water deficits are often open and complex.

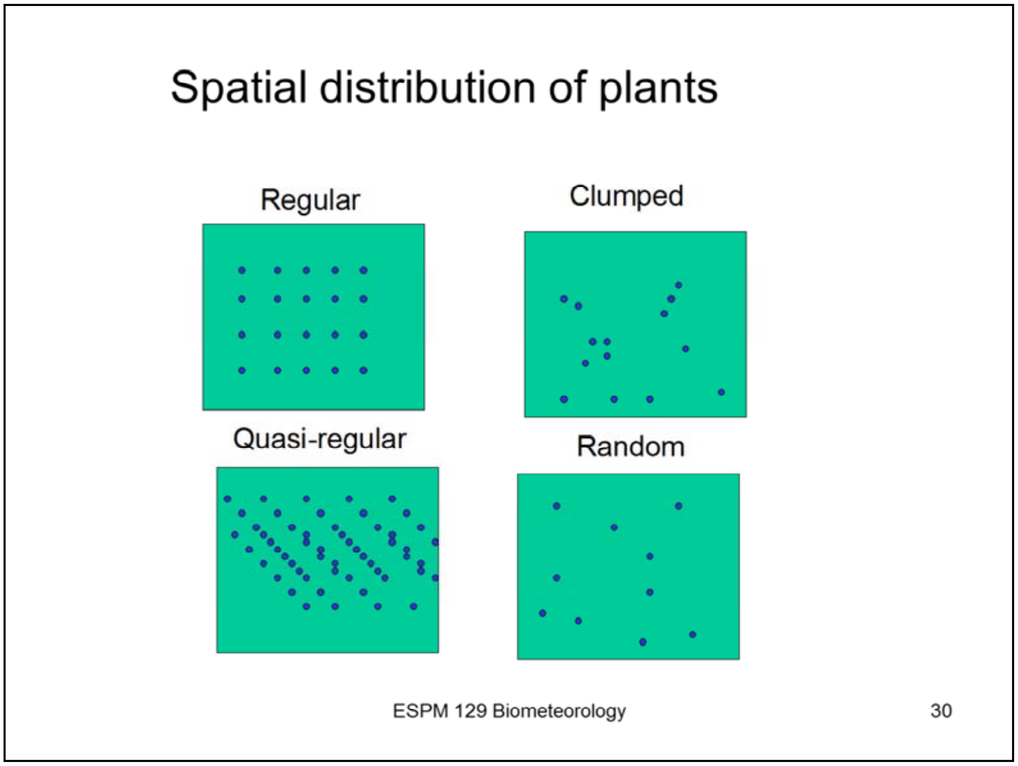
# Horizontal (spatial) distribution

- **Leaves**
  - Random dispersion
  - Clumped dispersion
  - Regular dispersion
- **Plants**
  - Random
  - Rows
  - Clumped

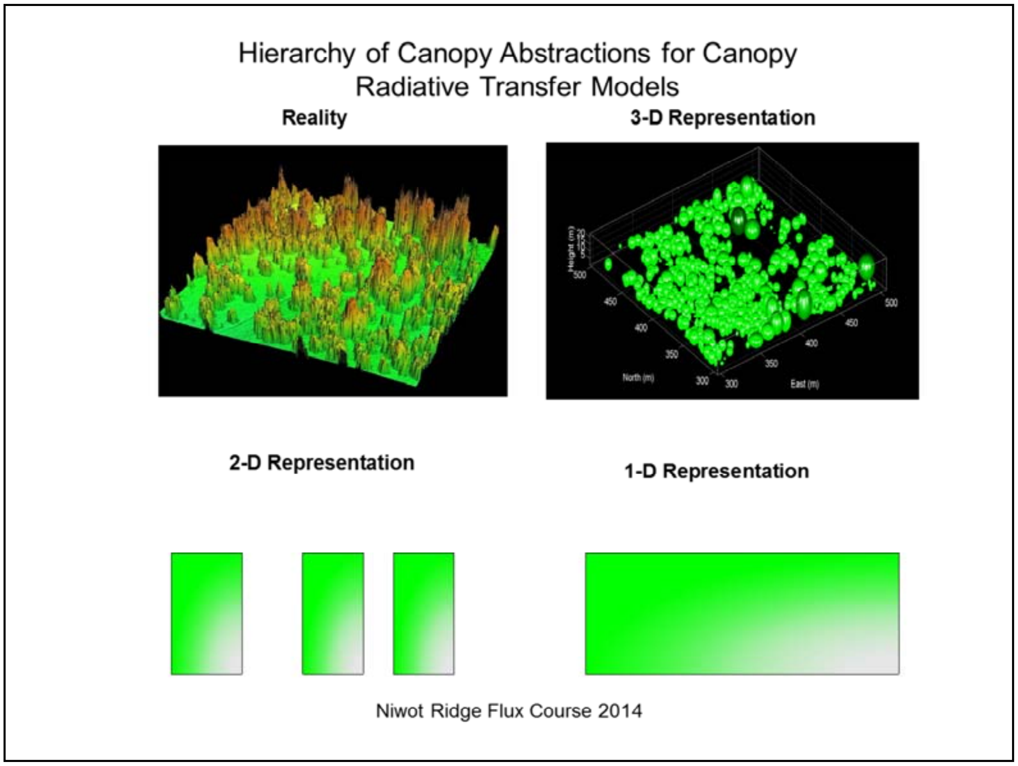




Depending on if the canopy is natural or managed, the distribution of leaves and plants may be random, clumped or regular. Random allows us to use simple statistical models to infer the transfer of light through foliage space. As plants and leaves become distributed in regular ways, we may need to rely on more geometrical models that simulate the edges of the crown and the space between crowns. Here more elabore and 3 dimensional models may need to be used.

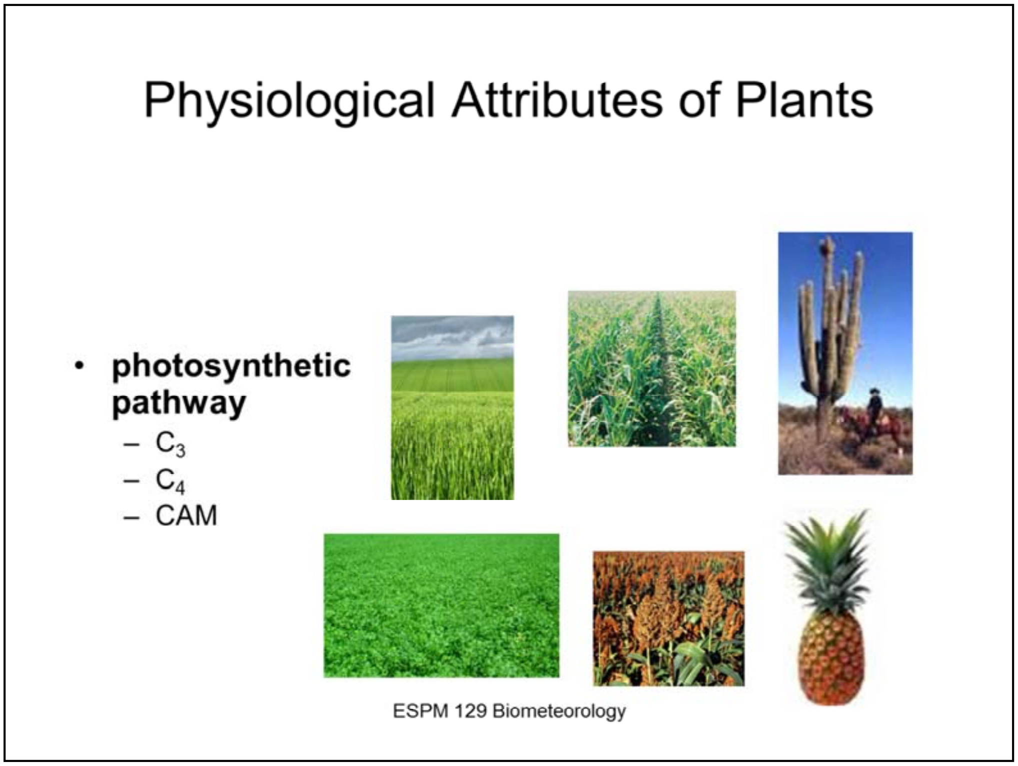



Typical spatial patterns of vegetation.  We want to know about regularity, clumping, randomness in terms of assessing sub grid variablity of regional climate and weather models.




The simplest case is a one dimensional, turbid medium, with randomly distributed leaves. Increasing complexity is a 2 dimensional representation, followed by a 3 d case. The 3d case can be explicit or assume crowns have shapes like ellipsoids, spheres, cones, cylinders.

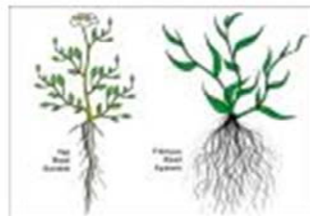
Lidar data is very important for telling us where the plants are and are not an how big they are. Such 3d treatment is intended to improve our ability to model light capture and light transmission through vegetation.




Plant tend to fix carbon dioxide via one of 3 pathways.  The C3 (Calvin-Bassham), C4 (Hatch-Slack) and Crassulacean acid metabolism. We will cover these topics later. But they are important as they have big impacts on stomatal conductance which affects the energy balance of a leaf and its water use, as well as rates of carbon uptake.

## Physical Attributes of Roots

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



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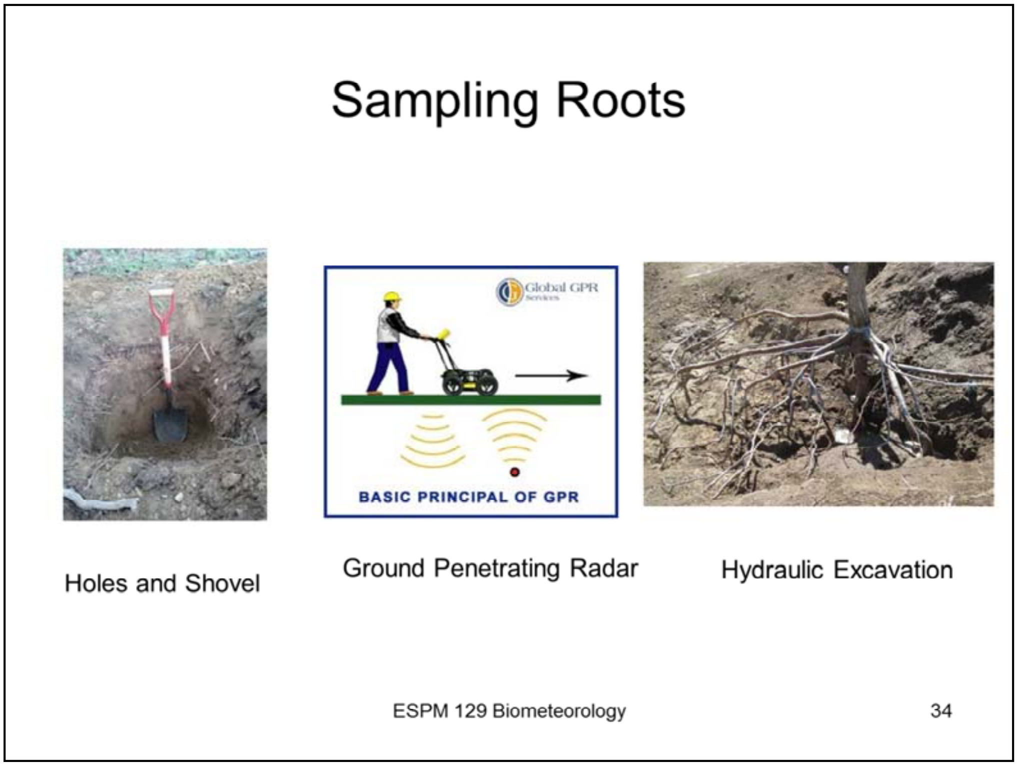
If we are to study the entire soil-plant-atmosphere continuum, we cannot forget about below ground resources, the roots, the water reservoir they tap, the nutrients they acquire and the biomass they sustain and how it supports microbial activity through lost exudates and fine root turnover.

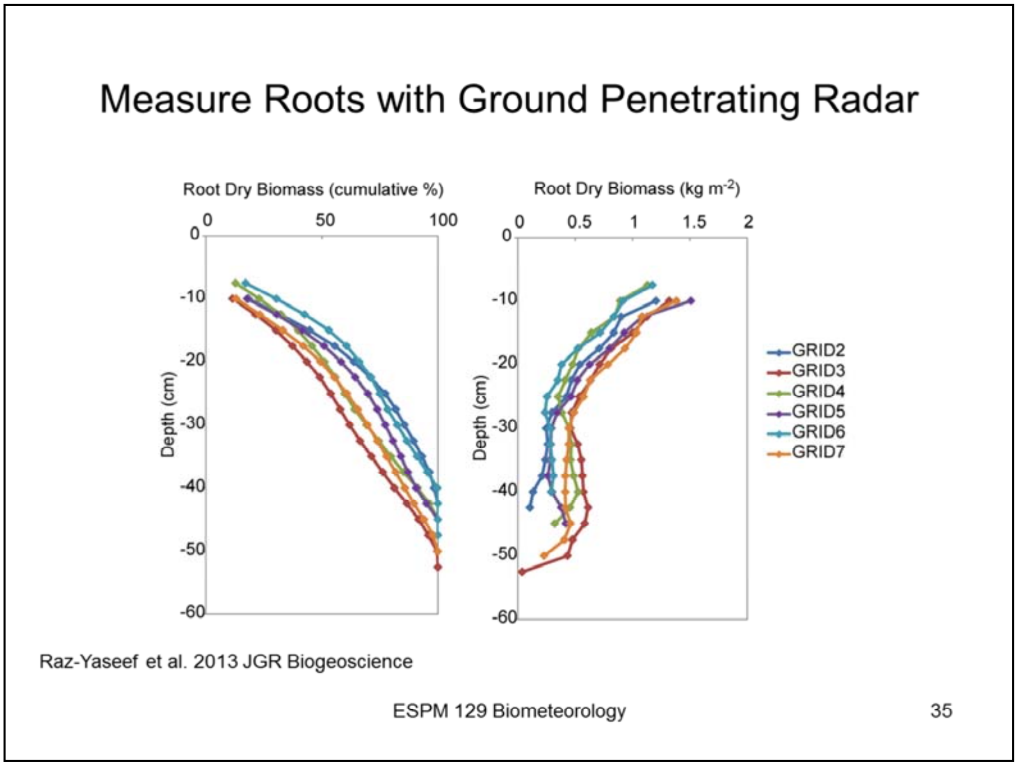



Destructive and non destructive means exist for sampling roots. Digging holes or blasting soils with hydraulic pressure are ways to sample them directly, and destructively. The area and amount of sampling is limited. Plus lots of work separating soil from roots. Ground penetrating radar is a remote and non destructive way to sample roots.

Digging holes is lots of work and subsequent measurements are needed to separate fine and coarse roots from soil. And in upscaling the pit data to the whole tree footprint.

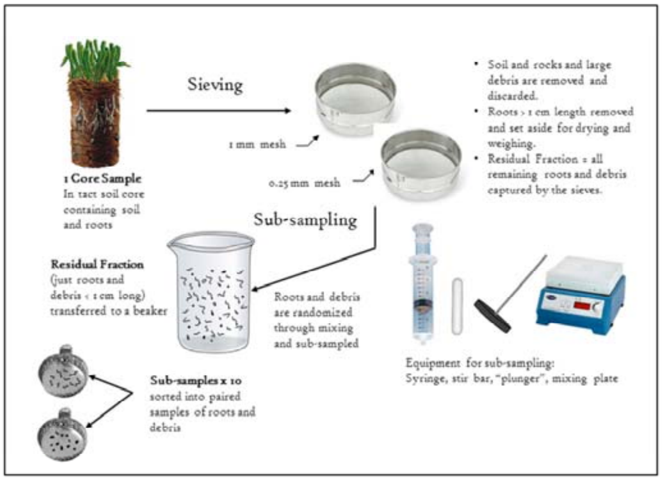
As an alternative, colleagues of mine tried to use TNT to blow holes in the ground. The smuggled a mix of chemicals into Argentina (obviously before 9/11), had a former weapons expert mix them together and form the explosive. The method failed and mostly damaged the roots.

Hydraulic means are very destructive and erosive. They also damage fine roots. But you see the integrated root ball.




We want to know the distribution of roots below the ground. It is often difficult and hard to dig, sample roots and separate them from soil. One remote sensing way is to use ground penetrating radar. It is best for looking at larger objects in the soil with different dielectric constants. Yet it is able to detect coarse roots well. Here is the distribution of roots below our oak trees. Notice that the root profile is concentrated in the upper 20 cm and it is not like an inverted tree.

## Sub Sampling Fine Roots




Koteen Baldocchi, 2013 Plant Soil

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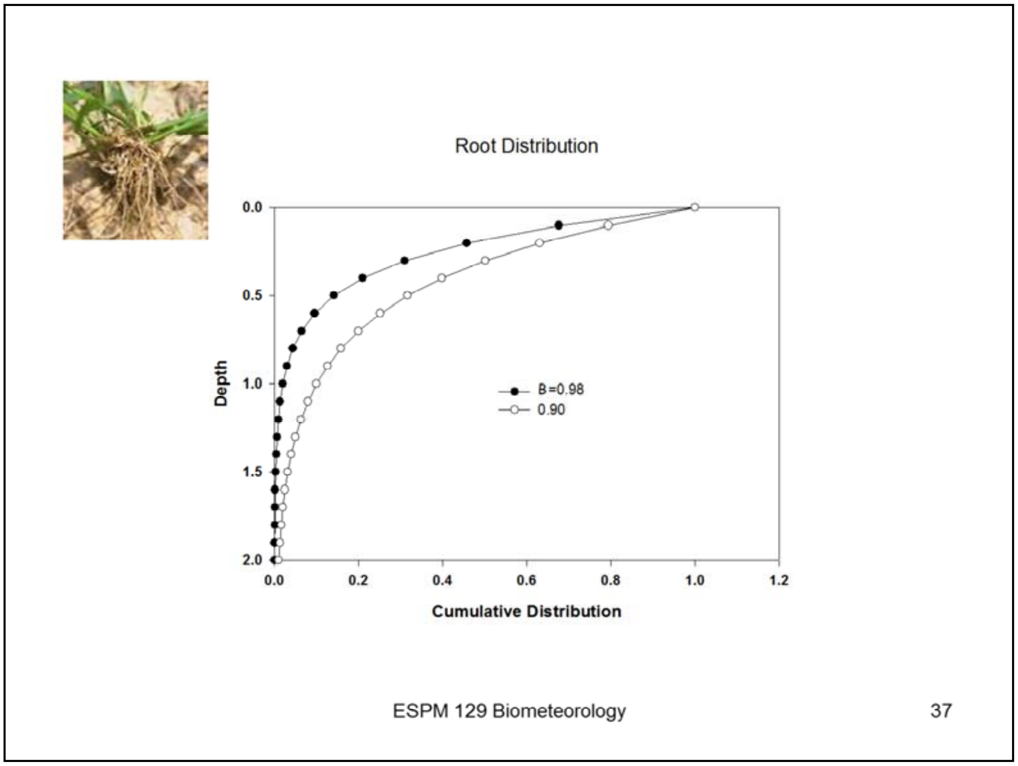
Sampling fine roots is important but vary time consuming and tedious; I spent nearly $20k in labor to collect a set of fine root data; but was a great part time job for a corps of Berkeley undergrads wanting lab experience. But, there has to be a quicker and better way. We borrowed on the idea of poll sampling of a small population to infer the state of the whole population




Cumulative distribution functions are useful for modeling roots. Simple models like this can be quite useful for translating root information to other applications, like computing mean soil moisture.

## Model parameters on cumulative root distribution ($Y=1-B^z$)

| Biome | B, total roots | % roots in upper 30 cm | B, fine roots | % roots in upper 30 cm |
|---|---|---|---|---|
| boreal forest | 0.943 | 83 | 0.943 | 83 |
| desert | 0.975 | 53 | 0.97 | 60 |
| sclerophyllous shrubs | 0.964 | 67 | 0.95 | 79 |
| temperate conifer forest | 0.976 | 52 | 0.98 | 45 |
| temperate deciduous forest | 0.966 | 65 | 0.967 | 63 |
| grassland | 0.943 | 83 | 0.943 | 83 |
| tropical deciduous forest | 0.961 | 70 | 0.982 | 42 |
| evergreen forest | 0.962 | 69 | 0.972 | 57 |
| tropical savanna | 0.972 | 57 | 0.972 | 57 |
| tundra | 0.914 | 93 | 0.909 | 94 |

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After Jackson (1999) 38

Jackson, Canadell and others have produced exhaustive surveys on root distributions from across the globe.

## 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, $P = dY/dz$

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I want to introduce you to the concept of weighted means. We need to know root distribution so we can compute a root weighted soil moisture. Why is this important. If you sample moisture with depth you may hit a deep layer where there are no roots and moisture is high. The arithmetic average will be biased high and not represent the soil moisture that the plant experiences. Instead we should compute root weighted distributions of soil moisture, for a more representative measure of what the plant is experiencing..true biometeorology.

# 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).

# Appendices

| Characteristic | Structural or Functional Attribute | Primary Impacts on Carbon, Water and Energy Fluxes |
|---|---|---|
| **Leaves** | | |
| Photosynthetic pathway | $C_3$,$C_4$,CAM, maximal stomatal conductance | $C_i$ , $G_s$ |
| Leaf size/shape | Needle/planar/ shoot; projected/surface area, penumbra/umbra | $G_a$, $P(0)$ |
| Leaf inclination angle distribution | Spherical, erectophile, planophile | $P(0)$ |
| Leaf azimuthal angle distribution | Symmetric/asymmetric | $P(0)$ |
| Exposure | Sunlit/shaded; acclimation | $C_i$, $G_s$, $\alpha$ |
| Optical properties | Reflectance,transmittance, emittance | $\alpha$ |
| Leaf thickness | Photosynthetic capacity, supply of $CO_2$ to chloroplast, optical properties, Stomatal conductance capacity | $C_i$ ,$G_s$, $\alpha$ |
| Stomatal distribution | Amphistomatous/hypostomatous | $G_s$ |

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Various attributes of plant canopies and how they relate to an array of Biometeorological parameters like the probability of light transmission (P0), the boundary layer conductance of the air (Ga), reflectivity (a), stomatal conductance (Gs), the internal concentration (Ci)

| **Plants/Trees** | | |
|---|---|---|
| | | |
| Crown volume shape | Cone, ellipse, cylinder | ***P(0), $G_a$*** |
| Plant species | monoculture, mixed stand, functional type | ***P(0), $G_a$, $G_s$, $C_i$*** |
| Spatial distribution of leaves | Random, clumped, regular | **P(0)** |
| Plant habit | Evergreen/deciduous; woody herbaceous; annual/perennial | $\mathbf{G_a}$, $\mathbf{G_s}$, $\alpha$ |
| Plant height | Short (< 0.10 m) tall (> 10 m) | $\mathbf{G_a}$, $\alpha$ |
| Rooting depth | Accessible water and nutrients, plant water relations | $\mathbf{G_s}$ |
| Leaf area/sapwood ratio | Hydraulic Conductivity | $\mathbf{G_s}$, $\mathbf{C_i}$ |

| | | |
|---|---|---|
| *Forest Stand* | | |
| | | |
| Leaf area index | Open, sparse, closed | **P(0), $G_s$, $G_a$** |
| Vertical distribution of LAI | Uniform, skewed | **$G_a$, P(0)** |
| Seasonal variation of LAI | Evergreen/deciduous; winter or drought deciduous | **$G_a$, $G_s$** |
| Age structure | Disturbed/undisturbed; plantation; agriculture; regrowth | **$G_a$, $G_s$, P(0)** |
| Stem density | Spatial distribution of plants | **$G_a$**, $\alpha$ |
| Woody biomass index | Amount of woody biomass | **$G_a$, P(0)** |
| Topography | Exposure, site history, water balance | **$G_a$, $G_s$** |
| Site history | Fires, logging, plowing, re-growth | $G_a$,$G_s$,$C_i$, $\alpha$ |

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| Parameter | grass/ cereal | shrub | Broad-leaved crop | savanna | Broad-leaved forest | needle leaved forest |
|---|---|---|---|---|---|---|
| LAI | 0-5 | 1-7 | 0-6 | 0-7 | 3-7 | 1-10 |
| fraction of ground cover | 1.0 | 0.2-0.6 | 0.1-1 | 0.2-0.4 | >0.8 | >0.7 |
| understory LAI | - | - | - | 0-5 | 0-2 | 0-2 |
| leaf normal orientation | erectophile | uniform | uniform | uniform/erectophile | uniform/ planophile / clumped | uniform/ planophile/ clumped |
| fraction of stems | - | 0.05 | 0.10 | 0.10 | 0.15-20 | 0.15-0.20 |
| leaf size (m) | 0.05 | 0.05 | 0.10 | 0.10 | 0.10 | 0.01 |
| crown size | | | | 4 by 4 | 10 by 10 | 7 by 7 |

| biome | albedo | Height (m) | Zo(m) | LAI max | Rooting Depth |
|---|---|---|---|---|---|
| Tropical forests | 0.12-0.14 | 30-50 | 2-2.2 | 4-7.5 | 1-8 |
| Temperate forests | 0.1-0.18 | 15-50 | 1-3 | 3-15 | 0.5-3 |
| Boreal forests | 0.1-0.3 | 2-20 | 1-3 | 1-6 | 0.5-1 |
| Arctic tundra | 0.2-0.8 | < 0.5 | < 0.05 | 0-3 | 0.4-0.8 |
| Mediterranean shrubland | 0.12-0.2 | 0.3-10 | 0.03-0.5 | 1-6 | 1-6 |
| Crops | 0.1-0.2 | variable | variable | 4 | 0.2-1.5 |
| Tropical savanna | 0.07-0.4 | 0.3-9 | variable | 0.5-4 | 0.5-2 |
| Temperate grassland | 0.15-0.25 | 0.1-1 | 0.02-0.1 | 1-3 | 0.5-1.5 |
| desert | 0.2-0.4 | < 0.5 | < 0.05 | 1 | 0.2-15 |

| biome | Max $g_s$ | $g_a$ | Max $CO_2$ flux, day | Max $CO_2$ flux, night | RUE |
|---|---|---|---|---|---|
| Units | mol $m^{-2}$ $s^{-1}$ | mol $m^{-2}$ $s^{-1}$ | $\mu$mol $m^{-2}$ $s^{-1}$ | $\mu$mol $m^{-2}$ $s^{-1}$ | G(DM)/ MJ (PAR) |
| Tropical forests | 0.5-1 | 0-4 | -25 | 5-8 | 0.9 |
| Temperate forests | 0.5 | 1-4 | -25 | 1-6 | 1 |
| Boreal forests | 0.2 | 10 | -12 | 0-4 | 0.3-0.5 |
| Arctic tundra | | | -0.5 to -2 | 1-2 | |
| Mediterranean shrubland | 0.5-1 | | -12 to -15 | 6-7 | |
| Crops | 1.2 | 1-3 | -40 | 2-8 | 1-1.5 |
| Tropical savanna | 0.2-1 | 0.1-4 | -4 to -25 | 2-5 | 0.4-1.8 |
| Temperate grassland | 0.4-1 | 0.2-1.5 | -13 to -20 | 0.5-4 | |