# Radiation Transfer in Environmental Science

## with emphasis on aquatic and vegetation canopy medias

# Radiation transfer in vegetation canopies
# Part I – plants architecture

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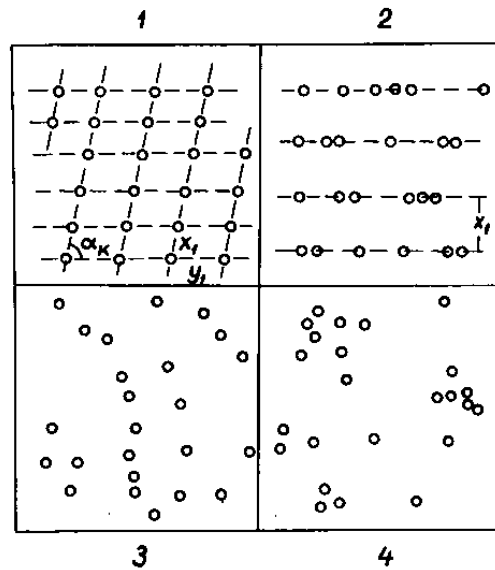
# *Vegetation and radiation* –
## *introduction*

♣ Photosynthesis, the main form of energy production to the biosphere, is a photochemical process of harvesting light by plant tissue (and CO2 from the atmosphere) that leads to formation of C-H chains used as energy sources & for building the life's materials (cells, proteins, DNA...).

♣ Plants growth and success are strongly dependent on harnessing light according to the light regime in canopies; plants are competing for light, types and location in ecosystem depends on light intensity (e.g., understory biome differ from the over story), biomass yield is highly dependent on light, while during sever conditions plant develop mechanisms for avoid excess light (common in very cold or very dry conditions).

♣ Understanding and modeling light regime inside vegetation canopies is used in many fields: in agriculture (e.g., estimation crops' yield, water consumption, pests development, etc.), for assessing natural plants processes, studying vegetation effects on climate and the environmental conditions inside ecosystems.

♣ Understanding the interaction of light with canopies is used through remote sensing techniques to identify vegetation growth rate, conditions (e.g., plants' water stress, growth season length…), foliage leaf area and the like.

# The distinctive of radiation in vegetation canopies
## (compared with the atmosphere and oceans cases)

♣ **The size of vegetative elements which interact with radiation** (the phytoelements: leaves, branches, fruits…) **are much bigger than the wave lengths ($\lambda$) of radiation** (>3 orders for leaves of <mm). **The basic interactions** (such as scattering) **processes in air or water do not apply here** (e. g., Mie, Rayleigh…).

♣ **Optical properties differ from the water and air mediums and between the different phytoelements** (leaves vs. flowers…).

♣ **Phytoelements have a shape, they are either 'flat' or 'cylinder' or with other form with a given orientation in space; they mostly not 'sphere' as assumed for molecules or aerosols in atmosphere.**
**Light-phytolement interaction is a three angles problem** (the following class).

♣ **Canopies are not homogenous layers and the phytoelements are unevenly spread in the canopy space (both vertically and horizontally), forming heterogeneous medium for light to transfer through.**

# Architecture of plant stands

♠ For most vegetative species leaves are the dominant phytoelements that interact with radiation; leaves surface area is 80-90% of the plants total area).

♠ Vegetation ecosystem surface cavers ranged from almost bare soil (e. g., desert) to full cover landscape, may have multi-layers canopy, such as in rain- or boreal- forest. Most natural ecosystems composed of a combination of different plants type and age that are mixed together.
Multi-layers could be made of trees and understory shrubs both over the same surface.

♠ In nature even the description of 'pure stand' in space is a challenge. Pure stands means plants of the same species (e. g., Aleppo Pine forest) and can be found mostly in cultivated stands (agricultural crop stands, afforestations…).

♠ We can envision 4 types of surface covers made by a pure stand:

Fig. 2. Four types of plant dispersion with equal density $N_P = 24$.
1 – regular dispersion (square sown crop); 2 – semi-regular, tending from regular to random (row crop); 3 – random (broadcasting); 4 – clumped, tending from random towards crowding (natural stands).

**Possible surface covers by pure stand:**

Ross J. 1982

$N_p$ - **Plant's canopy density around point P (number of per surface area – plants/m$^2$)**

1) **Regular dispersion (even spread row crop): $x_1$ and $y_1$ are the distances between plants, $\alpha$ angle between rows.**

   **Maximum surface closure when stand's basal area = $x_1/2$ and $\alpha = 60°$.**

3) **Random dispersion is given by binomial formula:**

$$p(m) = C_N^m \left( \frac{N_p}{N} \right)^m \left( 1 - \frac{N_p}{N} \right)^{N-m}$$

P(m) probability for density m (1, 2..N) around point P.

N- maximum possible density, and:

$$C_N^M = \frac{N(N-1)...(N-m+1)}{m!}$$

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## *dispersion of plants in field*

- **Stand arrangement in space could vary from regular dispersion, to random distribution.**



**Regular arrangement, mostly crop stands**

- **Several vegetation types (even of different kinds) could occupy the same volume space.**



**Fisheye image of fine trees crown at Yatir**

# *Surface cover by plants*

♣ There is no satisfactory and fairly simple mathematical method to describe dispersions (2) and (4) (previous page); and although it is an important characteristic of ecosystem structure, quantitatively dispersion can only be attained to the extreme cases: regular and random dispersions

♣ Multi-species random covers is presented as superposition of the individual species.

♣ It is common to treat vegetation ecosystem as made of horizontal layers, one above the other to the canopy top, each layer filled with foliage elements. Optical properties is attributed to the layer u(z) of a given thickness, according to the layer height (z) above the ground:

u(z)

z

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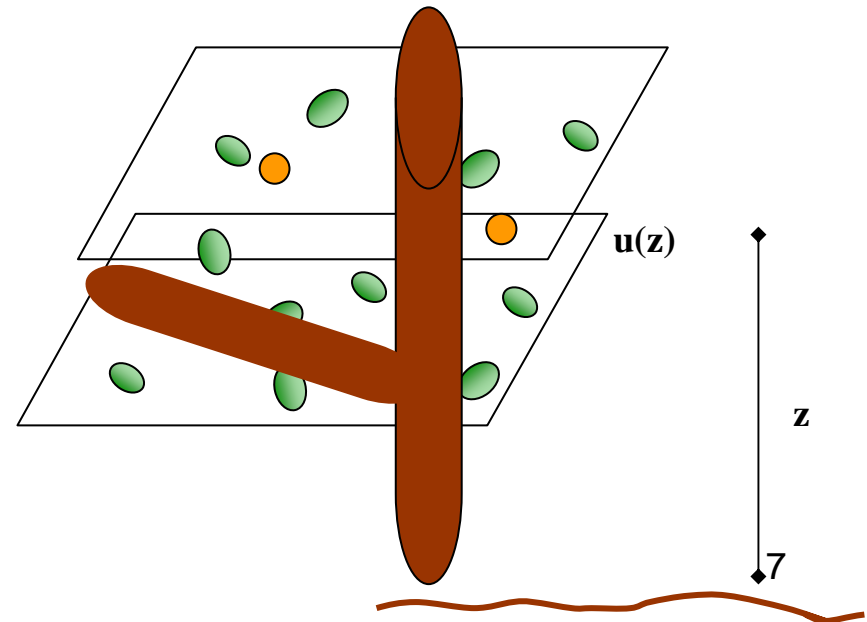
## *Foliage layer density*

♠ Consider first a volume V around point P(z), at height z in a plant. More general will be to use the P(x,y,z) notation, but lets assume here uniformity in the x and y directions.

♠ The volume contain *n* elements (leaves) with each leaf *k* having an area of Sk and then:

$$\sum_{k=1}^{n} S_K$$

is the total leaves' area inside volume V.

♠ The (leaf) layer area density $u_L(z)$ is:

$$u_L(p) = u_L(z) = \frac{1}{V(P)} \sum_{k=1}^{n} S_K$$

♠ Leaf area density (LAD) of a canopy layer defining the amount of leaf area in a layer volume and has the units of $m^2/m^3$.

♠ Note, although the term LAD is widely used (mostly in units of area per area) it is hardly measured8 and for good reasons….

♠ Leaf area means here the projected area on a ground of parallel leaf, thus it is equal to one side (silhouette) thin plate leaf area.

♠ Total leaf surface area could be considerably higher than the silhouette area, e.g., for needle leaves it's $\pi/2$ higher.
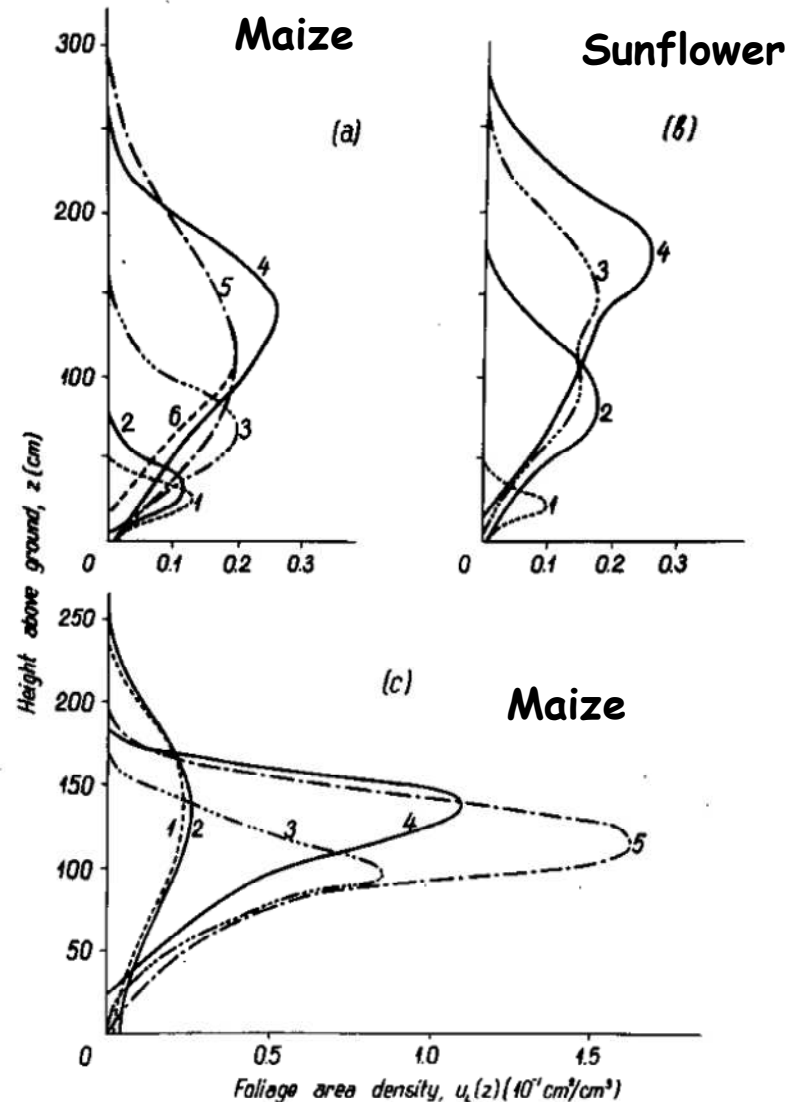
Fig. 15. Vertical distribution of foliage area density in maize and sunflower stands. (a) – maize, experiment No. 14, Tadjikistan, 1965, see text; (b) – sunflower, experiment No. 16, Tadjikistan, 1965. 1 – June 9, emergence of 16th leaf; 2 – June 27, emergence of 28th leaf; 3 – July 12, formation of inflorescence; 4 – August 14, ripening; (c) – maize stands with various density at the stage of tasseling or tassel flowering, see Table 5.1.

**Foliage area density at different age stages of maize and sunflower crops.**

**(Ross, 1982)**

Plants density is changing with time, growing conditions and environmental conditions.

Even for a pure stand LAD has irregular pattern.

# Leaf area index - LAI

♠ **Total leaf surface area is an important quantity, used for: quantitative photosynthesis rate and biomass production, water fluxes, energy exchange between leaves and the environment, others...**

♠ **Integrating u(z) from height z within the canopy to the uppermost part of a stand, $z_{top}$, gives the *downward cumulative leaf area index* above z of a plant:**

$$L(z, z_{top}) = \int_{z}^{z_{top}} u_L(z')dz'$$

**with units of foliage area to surface (ground) area - m$^2$/m$^2$**

♠ **Integration over the entire plant, from bottom to top, we obtain the plant leaf area index – LAI (although what actually measure is the plant area index – PAI).**

$$L(z_{bot}, z_{top}) = PAI = \int_{z_{bot}}^{z_{top}} u_L(z')dz'$$

♠ **The quantity LAI showing how many times the area of (one side of) leaves exceeds the basal area of plants above the ground.**
**The LAI ranged from close to zero (bare soil) to 10 and more, between biomes, according to vegetation age, season of the year and climatic conditions, cultivation practice, etc.**

## LAI measurements

♣ **A few methods exists today to measure LAI and PAI.**

♣ **Most common nowadays is using optical devices - the 'indirect method' approach: Those instruments infers LAI from the rate of light attenuation by the canopy's medium** (we will get to the equations connecting absorption to LAI later)**.**

♣ **Optical devices (few examples):**
**LAI2000 – made by the 'Li-Cor' company.**
**Probably the most used instrument, measure incoming hemispherical radiation at 320 – 490nm wavebands** (wave-band range with the lowest amount of scattered light by phytoelements)**, simultaneously above and below the canopy** (2 instruments)**, at five zenithal rings with viewing angles up to 74°;**
**Optional: add viewing caps to measure part of the hemisphere (90°, 180°..) enabling the measurements of a single tree, trees in a raw, etc.**



Typical Angular Response
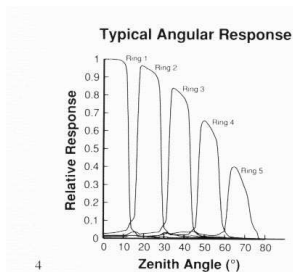
Each detector ring responds over a different range of zenith angles (left). The approximate field-of-view of each ring is simulated by the fisheye photo (right), where the colored lines represent angles with low response on the angular response graph. There is no response at zenith angles between 74° and 90°.

The LAI-2000 is an easy-to-use instrument for plant canopy structure measurements that is rapidly becoming an invaluable tool in a wide range of applications, including canopy productivity, forest vigor, air pollution deposition modeling, insect defoliation studies and remote sensing.

don't have to wait for a clear day, or for the sun angle to change. Further, measurements can be made under a variety of sky conditions; obscured sun is best, but measurements can be made on clear days using the proper measurement technique. Flexible instrument configurations also allow the LAI-2000 to be used in a variety of canopies ranging in size from short grasses to forests.

The LAI-2000 Plant Canopy Analyzer includes 1) The LAI-2070 Control Unit; 2) LAI-2050 Optical Sensor; 3) View Caps for the LAI-2050.

## *LAI measurements*

♣ LAI2000 instrument is highly sensitive to the light conditions thus good for early or late hours measurements, and known for underestimating the actual LAI in non random ecosystems (e.g., conifers).

TRAC instrument
In addition to measurements of the 'gap fraction', that is the windows where lights penetrates through the canopy (as LAI2000 works), TRAC measures the 'gap size distribution' along transect. TRAC uses the additional information coming from the GSD to quantify the effect of canopy clumping on the indirect measurements.
TRAC is considered the most accurate instrument, so probably combining LAI2000 to estimate the leaves' zenithal angle and TRAC gives the best description.



Jack Pine, 1365-y367, July 24, 1994
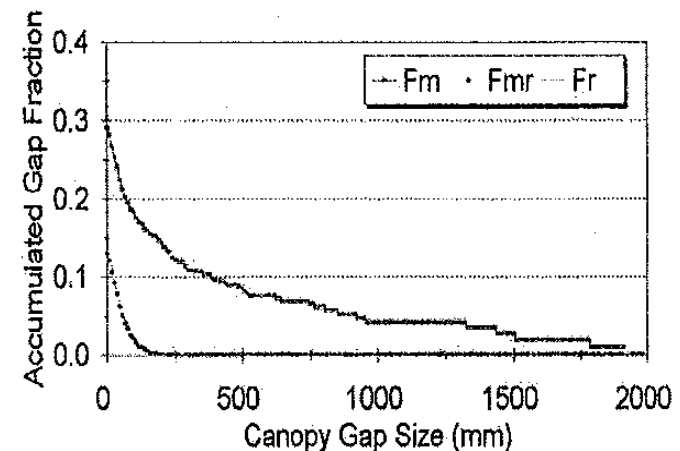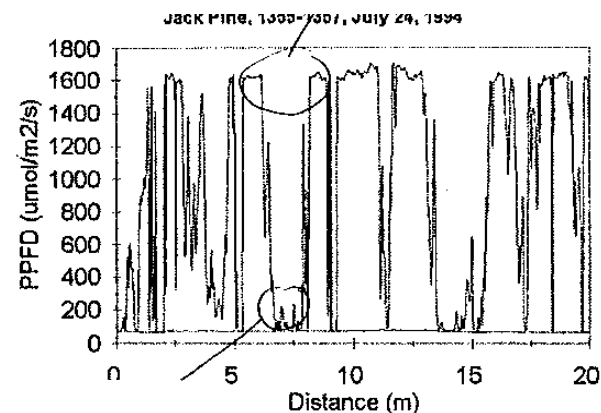
# *Other Methods*

<u>The 'direct method' approaches</u>

o For trees – developing alomatric equations which correlations between 'easy measured' variables to the leaf area, such as correlation between stem diameter at breast height (DBH) and trees' heights (H) to LAI.
These require cutting trees (distractive method), collecting all leaves and weighing their mass, sampling the correlation between leaves area (instrument exist) and weight, multiplying for the total weight to get the total leaf area and correlating to DBH and H.

o For understory vegetation – collecting all leaves at small plots (e. g., 1x1 m$^2$ area), weighing and measuring the leaves area, expanding for the whole field.

o Inferring LAI from falling leaves – this approach required to collect falling leaves for at least an annual cycle. In case the leaves life cycle is more than a year estimation of the leaves cycle is needed (e.g., conifers).

o Others approaches exist...

<u>Notes</u>

o The direct methods is used to calibrate for the indirect methods.

o How LAI is distinguished from PAI in the indirect approach is not well defined.

o The accuracy of the various methods is around 10-20%...

# Phytoelements arrangement in canopies.

♠ **Diverse stand shapes exist in nature (cylinders, cones, spheres, etc.)**

♠ **Foliages in canopies are grouped in several levels (next slide).**

♠ **Shapes and arrangements of leaves in stands:**
   **\* different species hves different leaf shapes - flat or curved, cylinder, half sphere, others.**
   **\* relative to the stand size (heights and width) leaves could be small (e.g., conifers) or big (e. g., Bananas).**
   **\* Leaves are pointing to all directions in space in a complicated manner.**
   **\* Leaves arrangement on stands differ between species.**

♠ **All leaf parameters change with stand age, environmental condition (e.g. season) and even with the wind speed.**

♠ **From the whole canopy to a single leaf:**

## *Foliages are grouped at several levels in stands*

♠ **Leaves can spread independently in a plant or can come in shoots (spices dependent).**
**Optical devices see shoot as a big leaf.**

♠ **Leaves are unevenly distributed on stands.**

♠ **In many stands leaves are arranged in 'groups'.**



**Whirl**

**Needles in a shoot**

**Branches**

**Crown**

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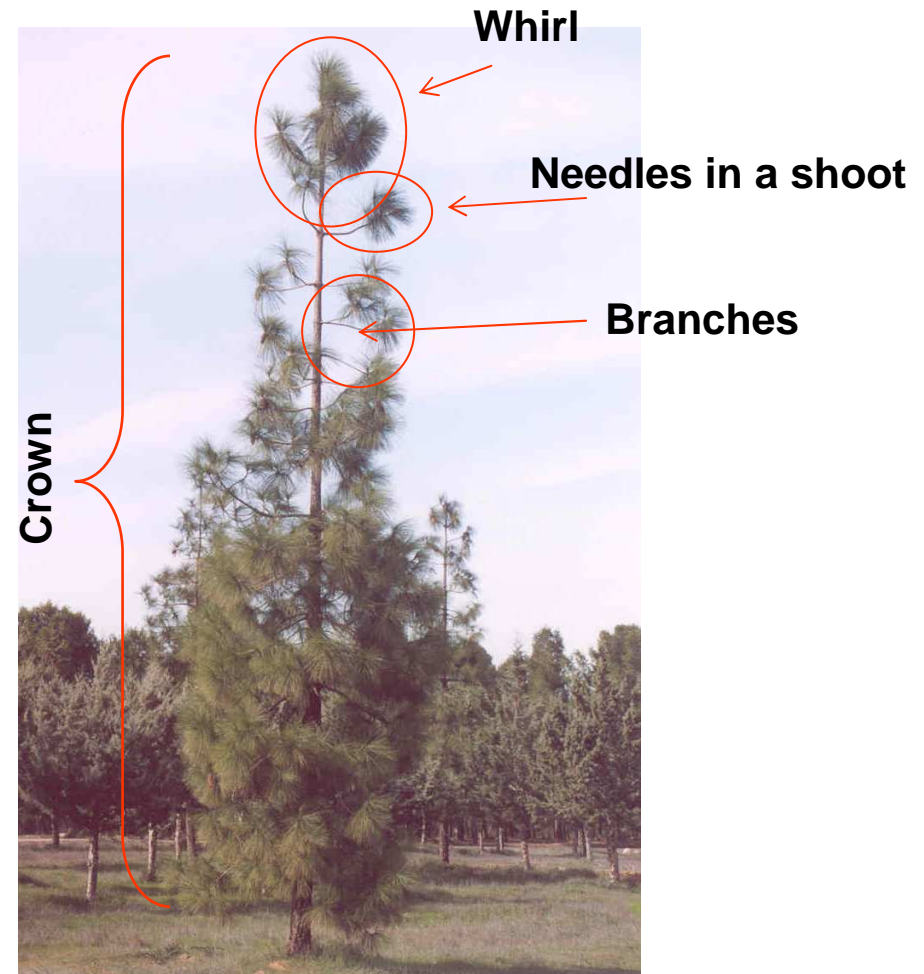
# Leaves' angles orientation in stands

**Flat, planophile leaves:**

**plagiophile leaves:**

**Flat, erectophile leaves:**

**Needles, randomly orientation:**