MODELING LEAF SPECTRAL AND DIRECTIONAL REFLECTANCE AND TRANSMITTANCE WITH A THREE-DIMENSIONAL LIGHT RAY TRACING APPROACH

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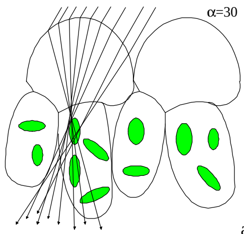
GOAL: to simulate the spectral and directional reflectance and transmittance of a typical dicotyledonous leaf

PREVIOUS WORK

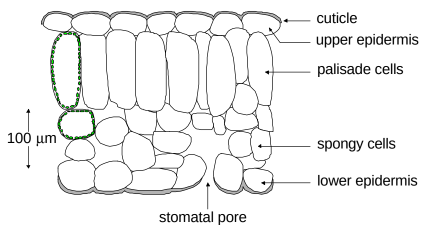
- at cell level: convex cells like epidermal cells may focus light (Haberlandt, 1914; Gabrys-Mizera, 1976; Bone et al., 1985; Martin et al., 1989)
- at leaf level: the internal leaf structure is described in detail; the optical constants of the leaf materials are known; using the laws of reflection, refraction, and absorption, the propagation of individual light rays is simulated (Allen et al., 1973; Kumar and Silva, 1973; Brakke et al., 1989)

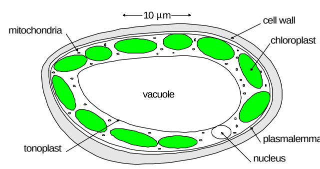
⇒ two-dimensional models



after Bone et al. (1985)

ANATOMY OF A TYPICAL DICOTYLEDON LEAF



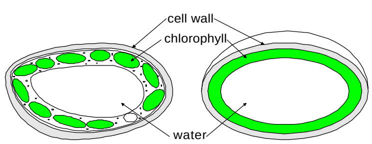


Leaf optical properties:

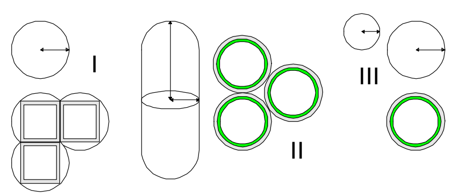
- light scattering → at microscopic scale: refractive index differences
  → at macroscopic scale: Rayleigh and Mie scattering
- light absorption → electronic transitions (chlorophylls, carotenoids, other pigments)
  → vibrations of polyatomic molecules (water, cellulose, lignin, hemicellulose, protein, starch, sugar, etc)

CONSTRUCTION OF THE LEAF

① **leaf cells = primitive objects (spheres, ellipsoids, cylinders,...)**

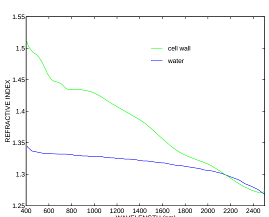


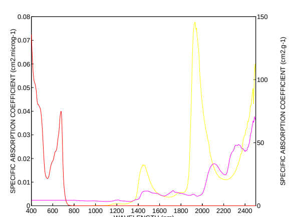
② **leaf tissues = connection and arrangement of the cells ⇒ Constructive Solid Geometry (CSG)**



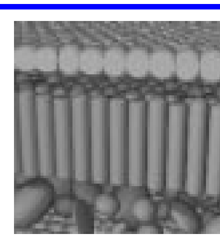
I epidermal cells
II palisade cells
III spongy cells

③ **optical properties of leaf biochemical components ⇒ the PROSPECT model**





COMPUTER REPRESENTATION OF THE LEAF



STATISTICAL DISTRIBUTION OF THE LEAF CONSTITUENTS

at cell level, one can calculate:
- the total volume
- the fraction volume of each constituent: cell walls, chlorophylls, water (Vw)
- the number of chloroplasts per cell (Nc)

at tissue level, one can calculate:
- the tissue thickness (e)
- the fraction of air spaces (Fa)
- the number of cells per unit area (N)
- the amount of leaf consituents per unit area (C)

at leaf level, one can calculate:
- the chlorophyll concentration in µg.cm^{-2}
- the equivalent water thickness in cm

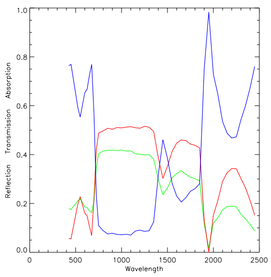
	Epidermis	Palisade parenchyma	Spongy mesophyll	whole leaf
e	25 µm	65 µm	50 µm	≈ 165 µm
Fa	19.6%	16.3%	45.0%	
N	320 000	513 200	(379 920)	1 533 120
Nc		40	25	
Cc		41 µg.cm^{-2}	19 µg.cm^{-2}	60 µg.cm^{-2}
Vw	73.9%	41.4%	54.9%	
Cw	0.00149 cm	0.00225 cm	0.00151 cm	0.00674 cm

SIMULATING THE LEAF OPTICAL PROPERTIES USING THE ***RAYTRAN*** MODEL

RAYTRAN = a Monte Carlo ray tracing approach designed to investigate radiation transfer problems in terrestrial environments over a variety of spatial scales (Govaerts and Verstraete, 1994)

the model relies on three hypotheses:

- incident radiation can be simulated with a finite number of photons which do not interact between themselves
- the medium can be described with geometrical primitives
- optical properties of the elements can be defined with probability distribution functions

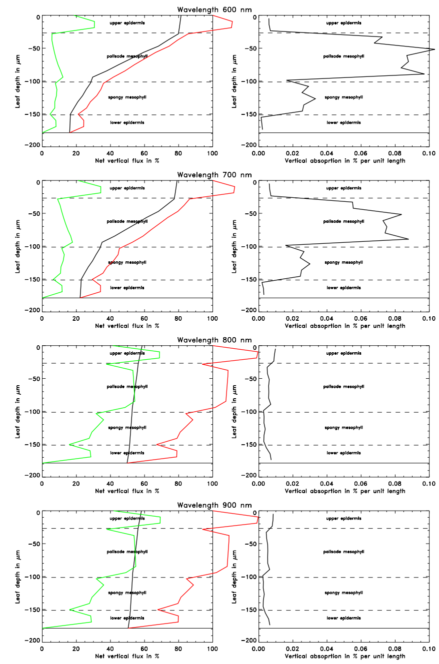


Reflectance (green)
Transmittance (red)
Absorptance (blue)

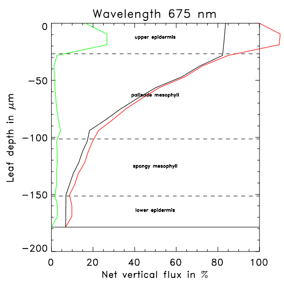
CONSEQUENCES

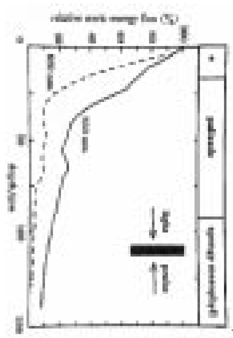
⇒ calculation of the upwelling (green), downwelling (red), and net flux (black) inside the leaf

⇒ calculation of the amount of light absorbed inside the leaf



Comparison with experimental data





Vogelmann et al. (1989)

CONCLUSIONS

- The three-dimensional structure of leaves is very important to their function:
  - ⇒ A first attempt to describe a plant leaf as an explicit absorbing and scattering three dimensional object
  - ⇒ A first attempt to apply a Ray Tracing model on such a medium

- In terms of leaf biophysical properties
  - ⇒ Reasonable description of the internal structure of a dicotyledon leaf with simple primitive objects
  - ⇒ Reasonable concentrations of leaf biochemical components (water and chlorophylls)

- In term of leaf physiology
  - ⇒ simulation of absorption profiles inside the leaf

- In terms of understanding ecological processes
  - ⇒ Simulations can be performed to examine the light harvesting consequences of various leaf structures and chemistry compositions
  - ⇒ Study the scattering and light harvesting properties of variations in leaf epidermal structure