Fourth International Workshop on Remote Sensing and GIS Applications to Forest Fire Management, Ghent, 5-7 June 2003.


Matisse, 1956, Cover for *Farbe und Gleichnis*

Application of radiative transfer models to moisture content estimation and burned land mapping

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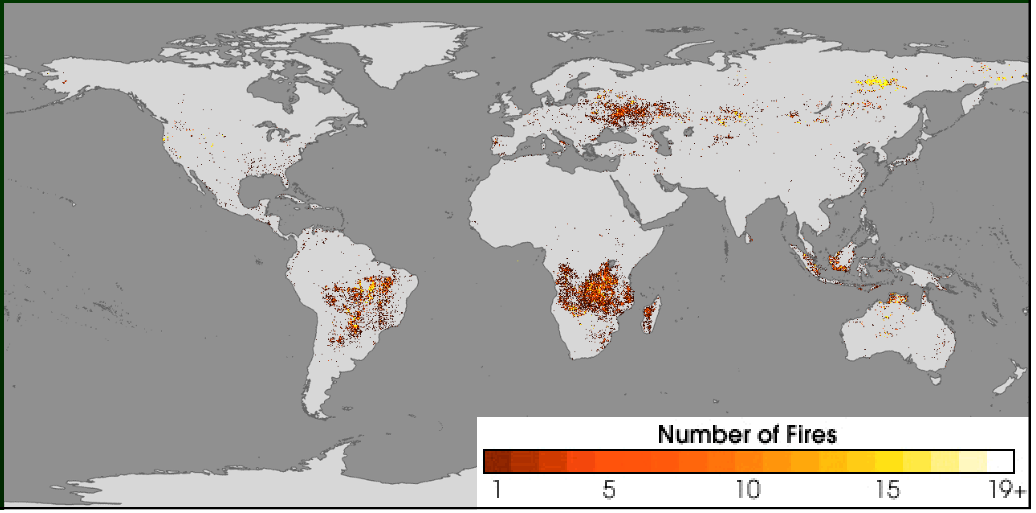
At a global scale, continents cover ~ **30%** of the Earth surface and vegetation covers ~ **65%** of the continents (forests 24%, prairies and tundra 15%, savannah 15%, crops 11%).

These biomes are crucial for the well-being of humanity. They provide foundations for life on Earth through ecological functions, by regulating the climate and water resources, and by serving as habitats for plants and animals. They also furnish a wide range of essential goods for humans.

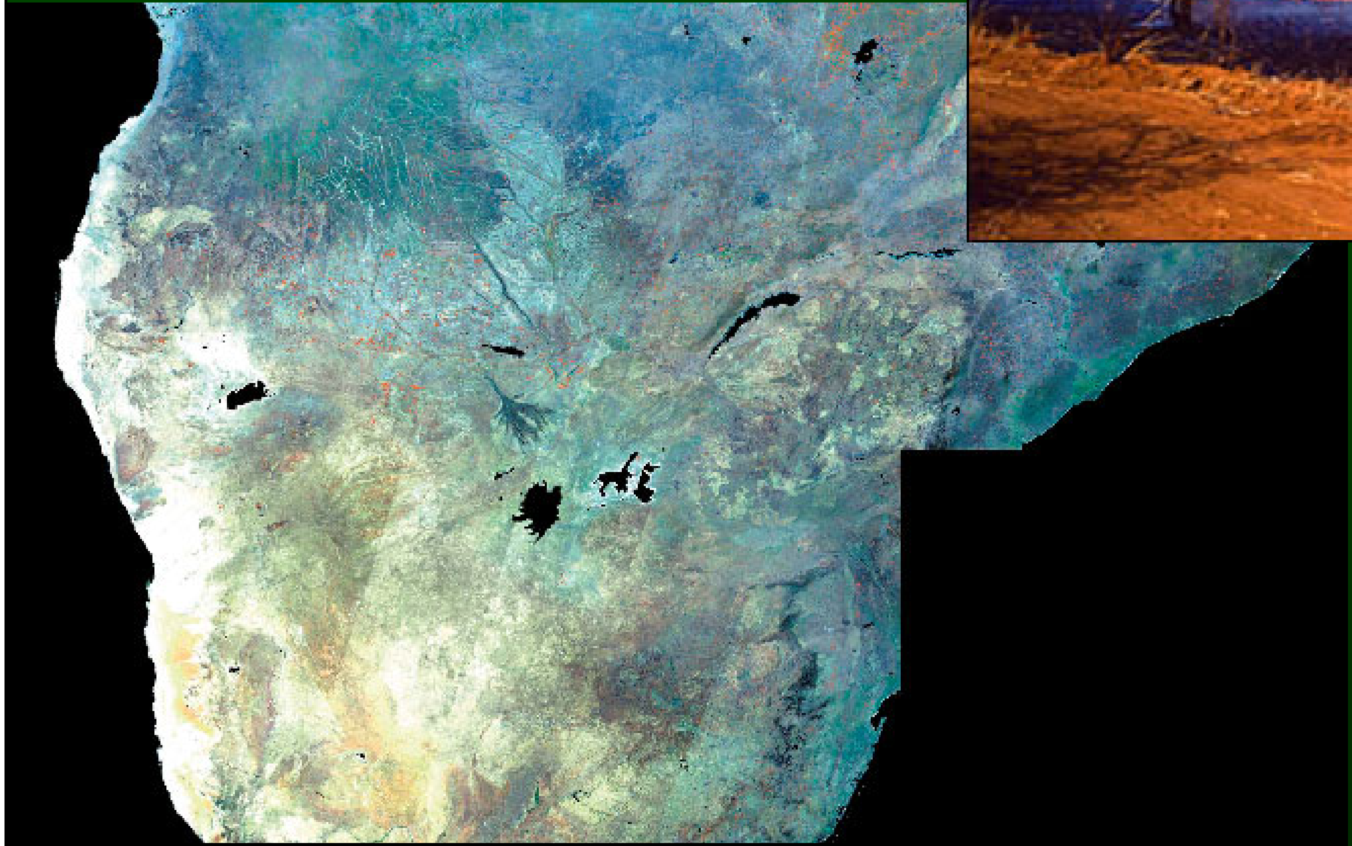
Virtually all kinds of vegetation are subject to wildfires: Thus, tropical rain forests that typically do not burn on a large scale were devastated by wildfires during the 1990s...

Wildfires during drought years continue to cause serious impacts to natural resources, public health, transportation and air quality (soot aerosols) over large areas.



Global fire map, August 15–22, 2002. ©Earth Observatory

One tool: Remote sensing (solar domain, thermal infrared, microwaves). Satellite systems have been used effectively to map active fires and burned areas.

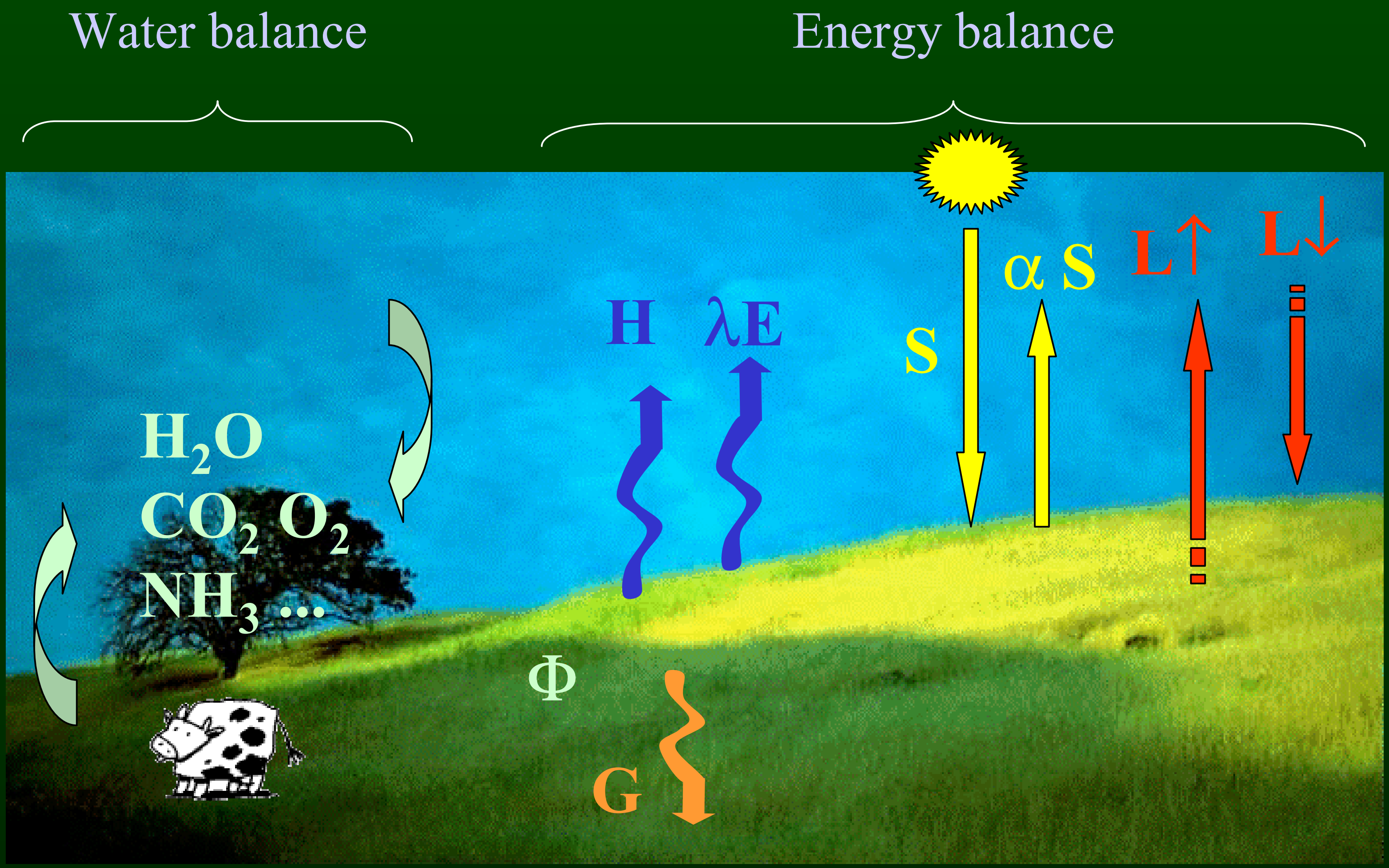


Monthly maximum NDVI composite computed from daily 500- m MODIS land surface reflectance data sensed August 28 to September 28, 2000

D.P. Roy, P.E. Lewis & C.O. Justice, 2002, *Remote Sens. Environ.*, 83:263–286.

Question: How to monitor the evolution of fire risk?

- use of meteorological variables to calculate the water balance
  → most important factor controlling aboveground primary production, and then fire frequency and intensity.



- direct measurement of vegetation water content

→ key factor in assessing flammability and combustibility where a sufficient amount of fuel accumulates.

Fuel Moisture Content

$$FMC = \frac{fw - dw}{dw}$$

Relative Water Content

$$RWC = \frac{fw - dw}{tw - dw}$$

Equivalent Water Thickness

$$EWT = \frac{fw - dw}{A}$$

FMC is routinely used by forest services to assess fire danger

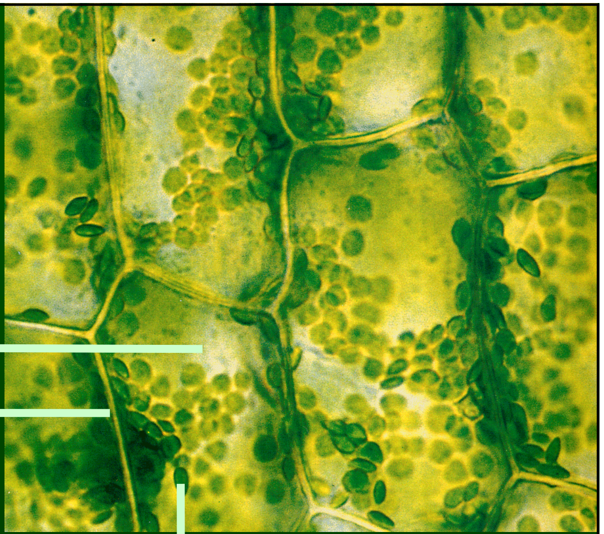
RWC is directly related to water potential

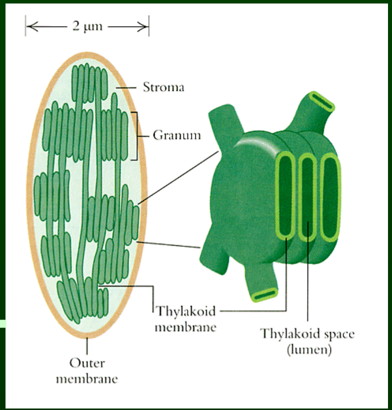
EWT is the hypothetical thickness of a single layer of water

Biochemical composition of leaves

A green-fresh leaf contains:

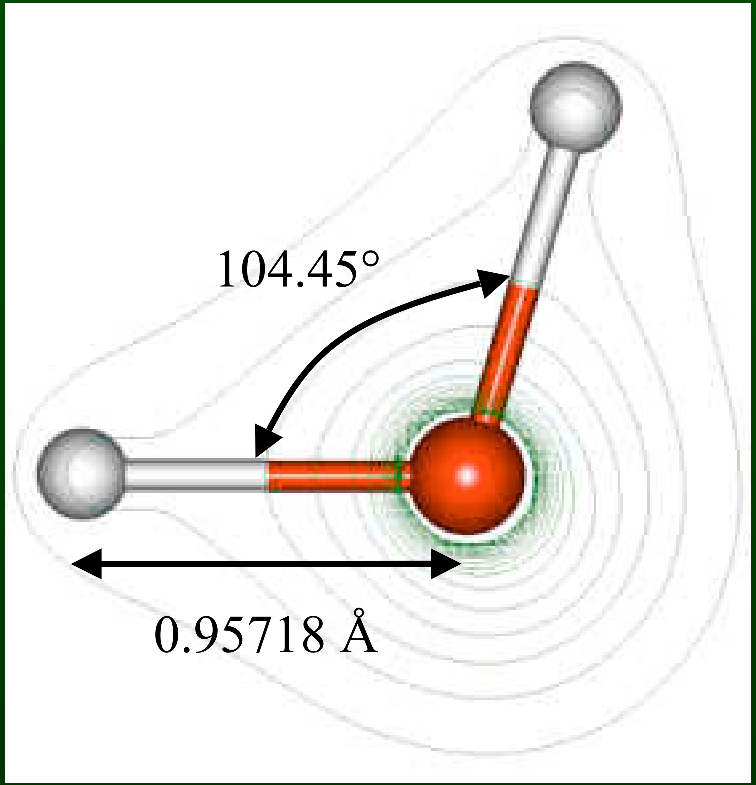
- water (vacuole): 90-95%
- dry matter (cell walls): 5-10%
  - cellulose: 15-30%
  - hemicellulose: 10-30%
  - proteins: 10-20%
  - lignin: 5-15%
  - starch: 0.2-2.7%
  - sugar
  - etc.
- chlorophyll *a* and *b* (chloroplasts)
- other pigments
  - carotenoids
  - anthocyanins, flavons
  - brown pigments
  - etc.

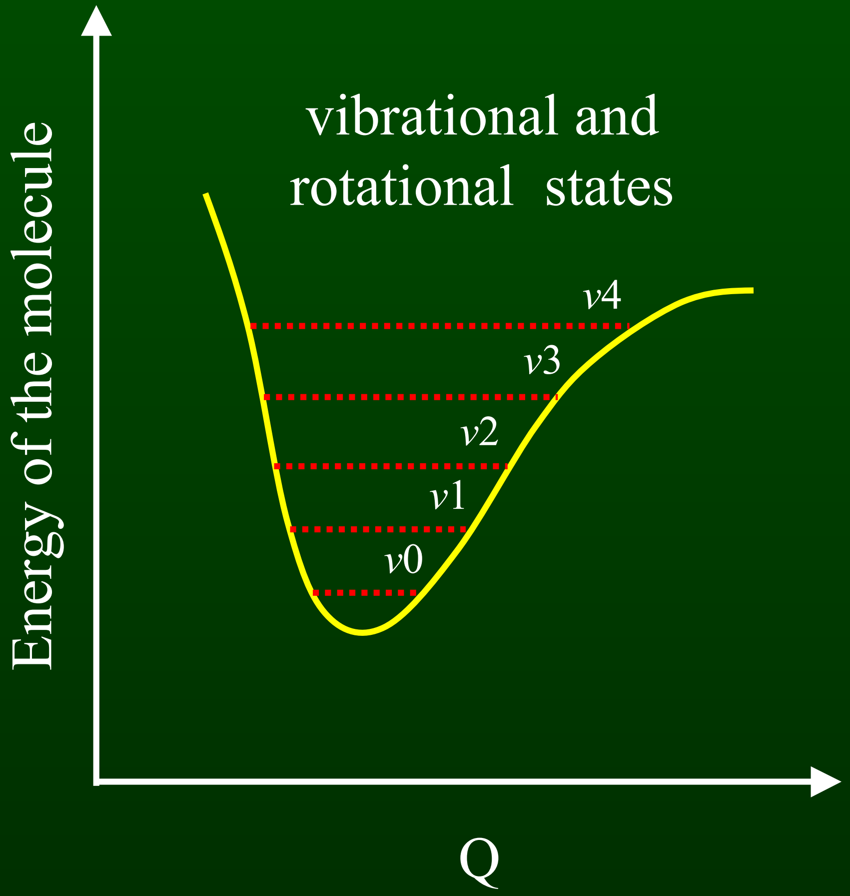




B. Hosgood, S. Jacquemoud, G. Andreoli, J. Verdebout, A. Pedrini & G. Schmuck, 1994, *Leaf Optical Properties EXperiment 93 (LOPEX93)*, Joint Research Centre, Ispra, Italy.

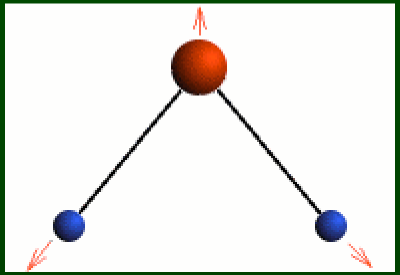
Water seems, at first sight, to be a very simple molecule, consisting of just two hydrogen atoms attached to an oxygen atom.



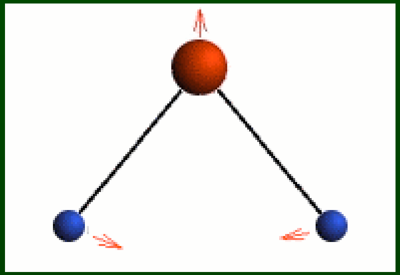


Molecule in the ground electronic state

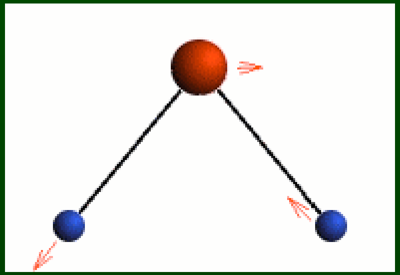
The molecule of water has three degrees of vibrational and rotational freedom:



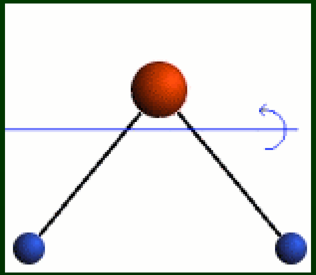
Symmetric stretching mode *v*1



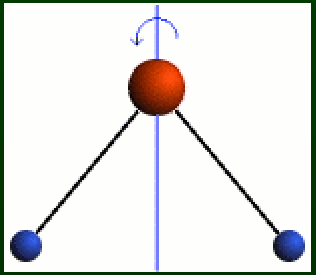
Bending mode *v*2



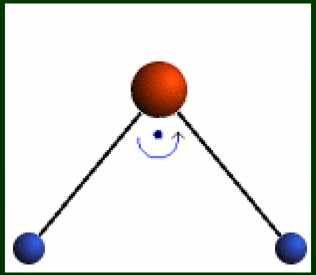
Asymmetric stretching mode *v*3



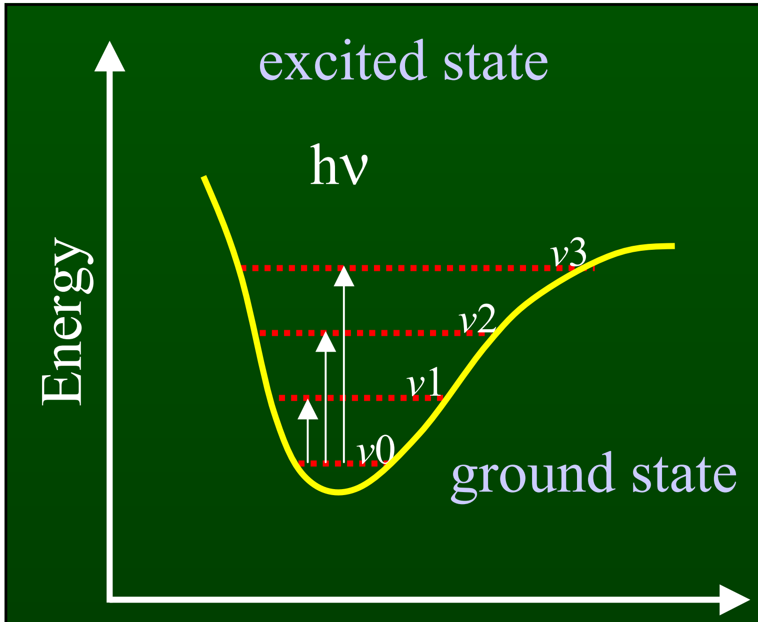
Rotational axis A



Rotational axis B



Rotational axis C

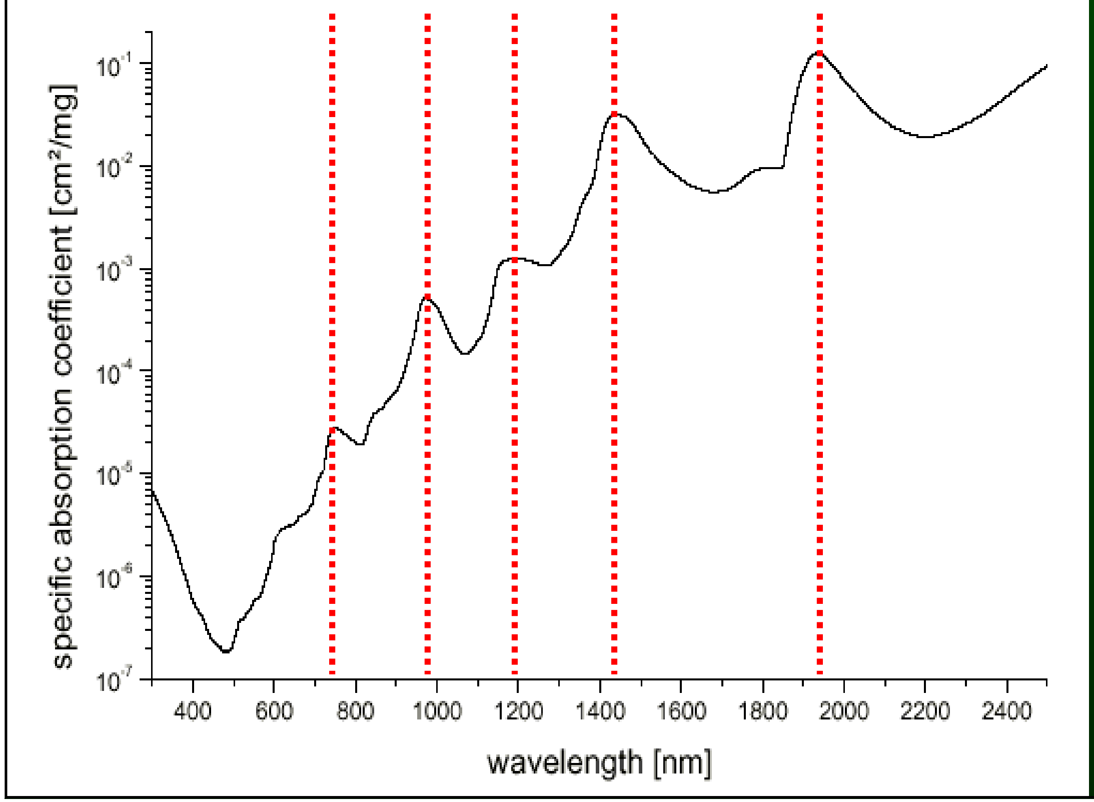


Transitions between vibrational levels can occur upon absorption of a photon. Sometimes these vibrational absorptions are very localized and can be associated with the stretching or bending of specific bonds.

Transition	Absorption intensity	Gas state	Liquid state	Solid state
*v*1	0.07	2.73 μm 3657 cm^{-1}	2.87 μm 3490 cm^{-1}	3.05 μm 3277 cm^{-1}
*v*2	1.47	6.27 μm 1595 cm^{-1}	6.08 μm 1645 cm^{-1}	
*v*3	1.00	2.66 μm 3756 cm^{-1}	2.90 μm 3450 cm^{-1}	

Most of the time, however, when two modes lie close in energy, they can mix.

Combination	Gas state	Liquid state
$v1 + v3$	0.739 µm	
$2\ v1 + v3$	0.970 µm	1.004 µm
$v1 + v2 + v3$	1.200 µm	1.272 µm
$v1 + v3$	1.450 µm	1.536 µm
$v2 + v3$	1.940 µm	1.990 µm

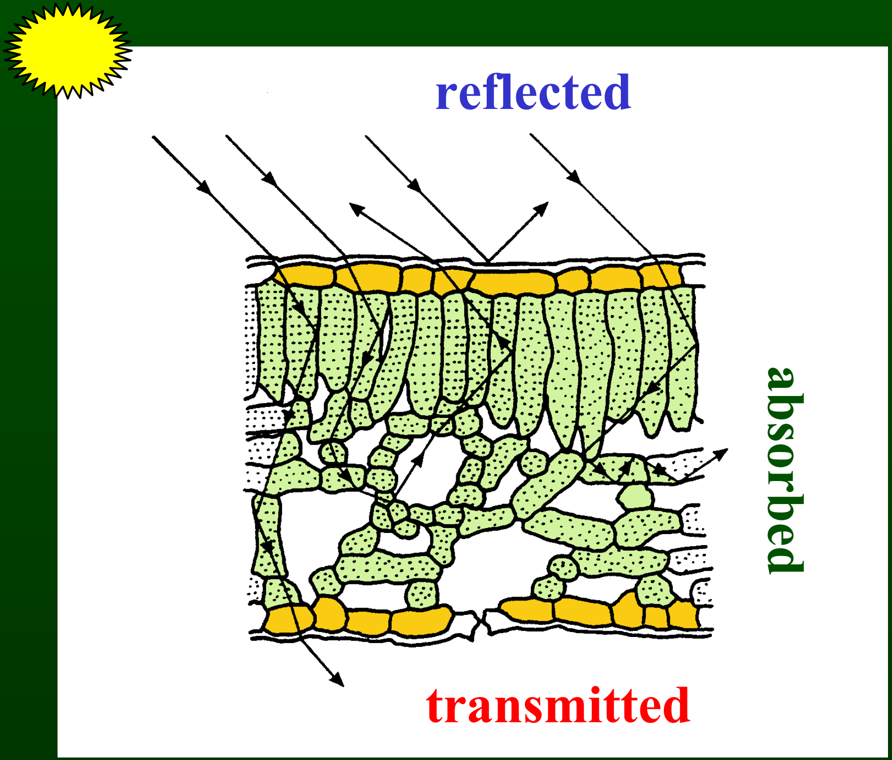


The observed infrared absorptions are combinations of the bending and streching of several bonds.

S.W. Maier, 2000, *Modeling the radiative transfer in leaves in the 300 nm to 2.5 m wavelength region taking into consideration chlorophyll fluorescence - The leaf model SLOPE*, PhD Thesis, 110 p.

Leaf optical properties

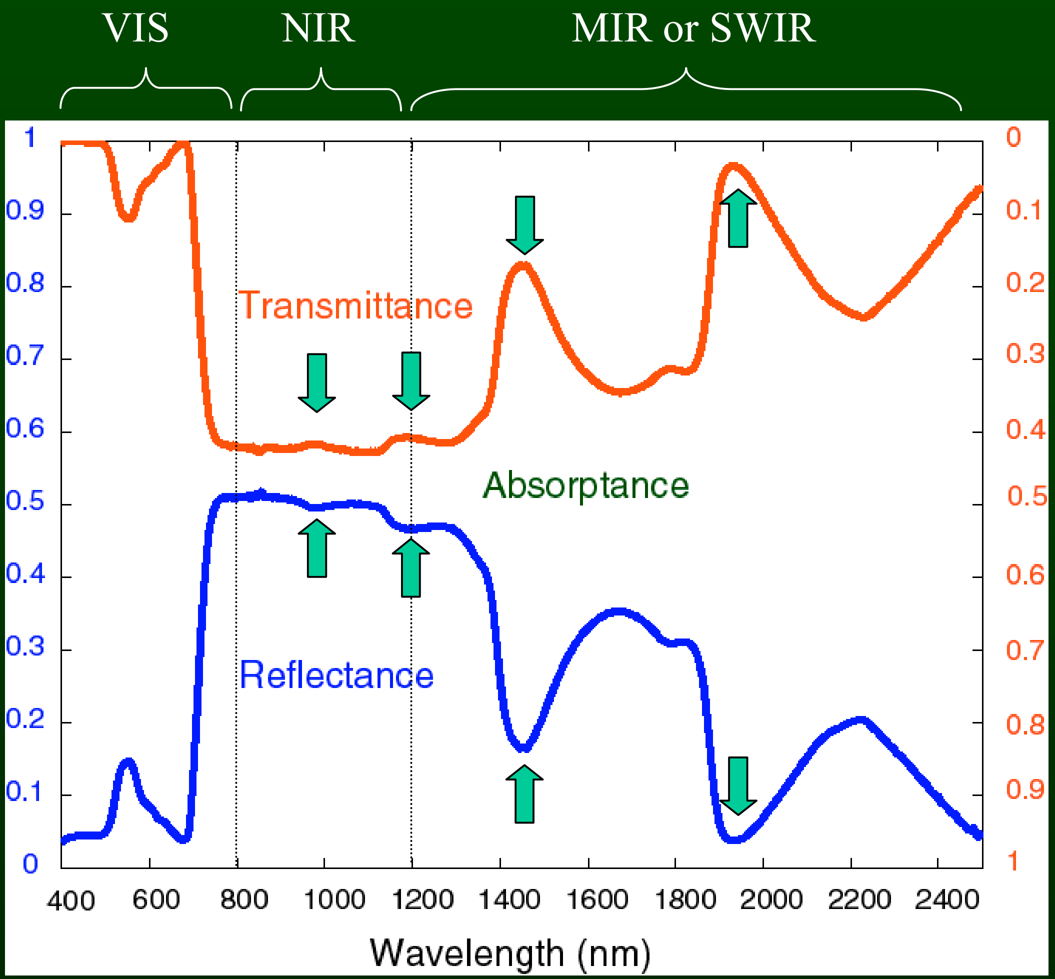
Tessa Traeger, 1997, Sight



T.R. Sinclair, M.M. Schreiber & R.M. Hoffer, 1973, *Agron. J.*, 65:276-283.

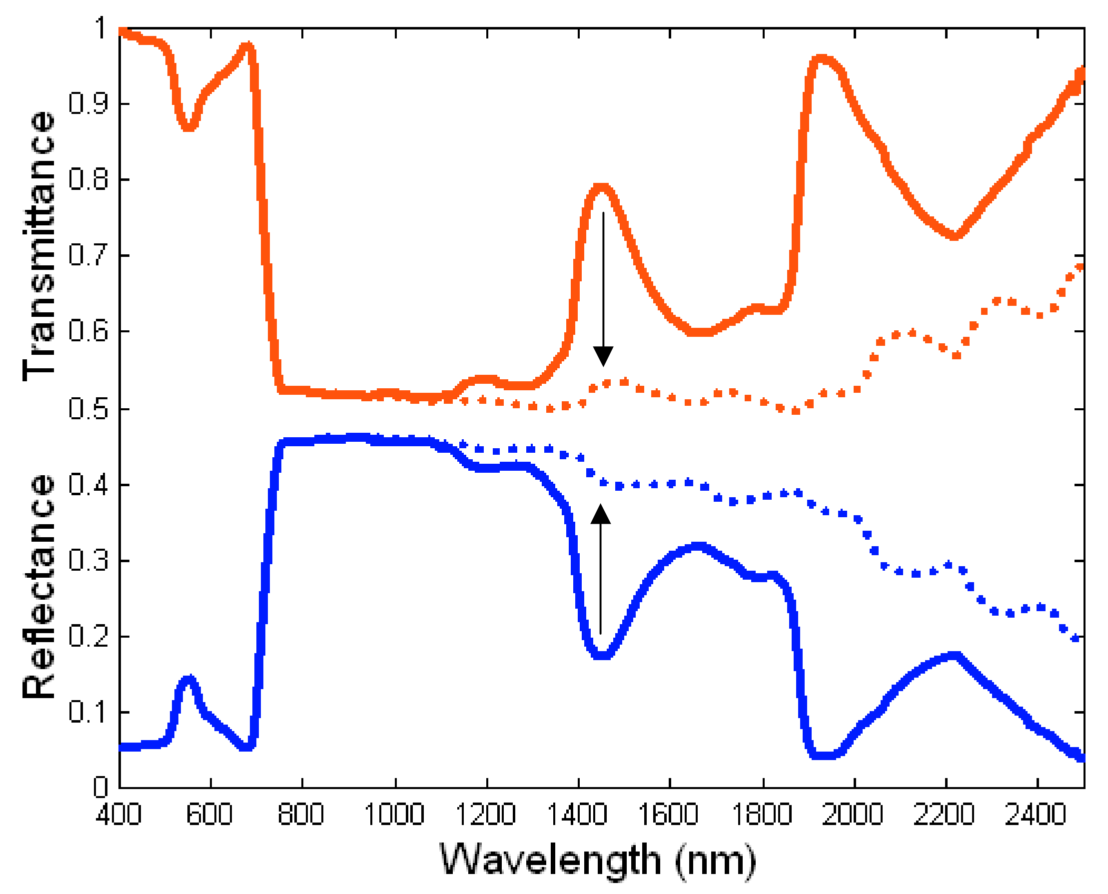
Reflectance ρ_f
Transmittance τ_f
Absorptance α_f

$$\rho_f(\lambda) + \tau_f(\lambda) + \alpha_f(\lambda) = 1$$



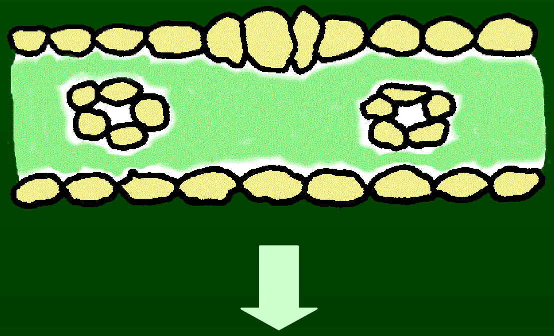
Trifolium pratense

Variations of leaf water content

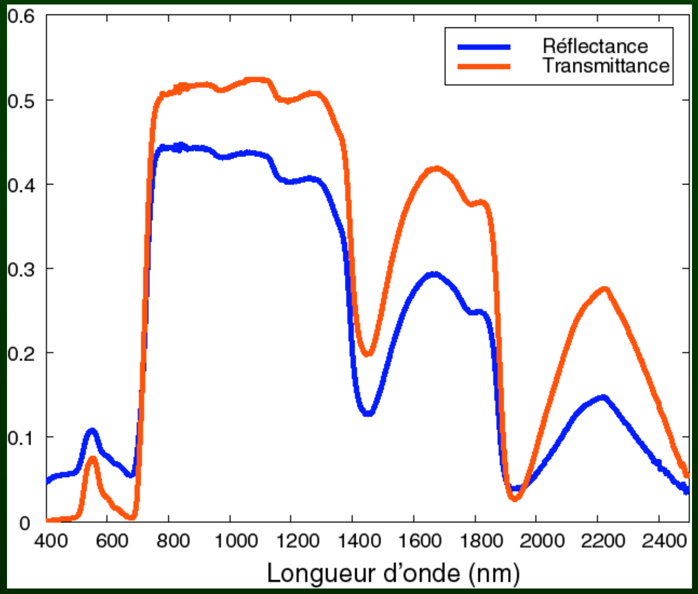


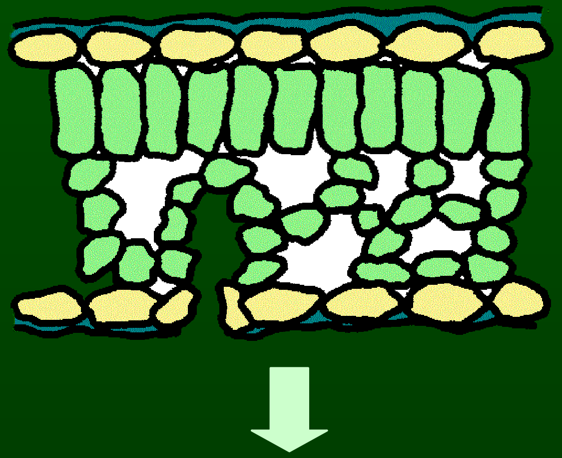
Fresh and dry poplar (*Populus canadensis*) leaves

Variations of leaf internal structure

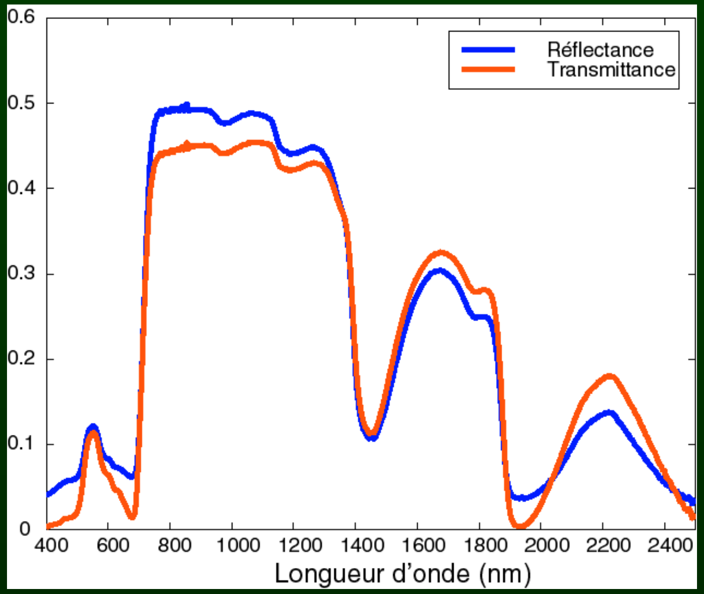


corn (*Zea mays*)



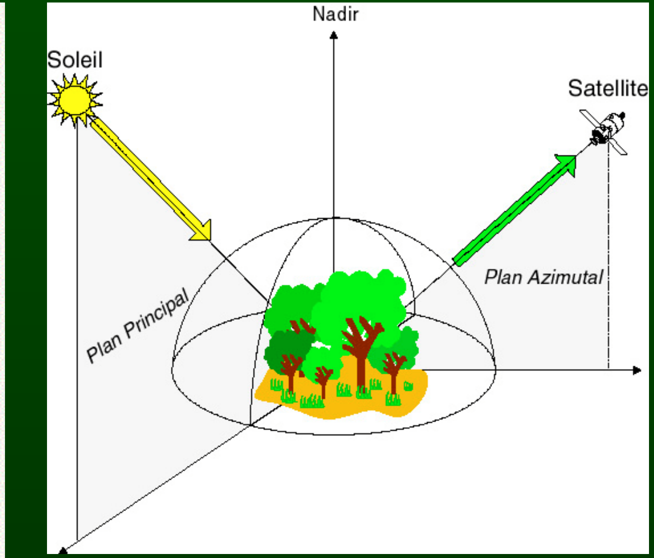


sunflower (*Helianthus annuus*)



Plant canopy reflectance

Magritte, 1963, La Belle Saison, CA

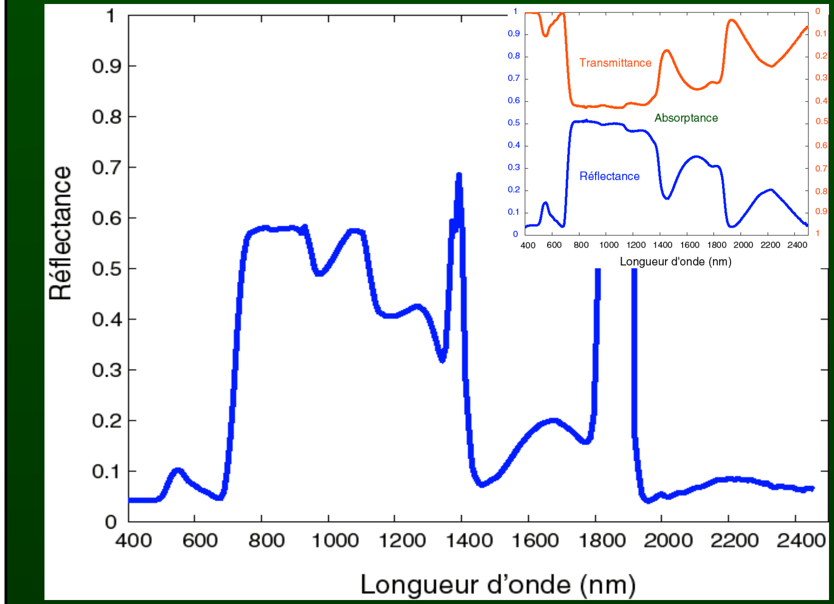


$$R = \mathbf{E}_r / \mathbf{E}_i$$

Plant canopy reflectance depends on:
- leaf optical properties
- soil reflectance
- Leaf Area Index
- plant architecture
- etc.

Plant canopy reflectance is also a function of:

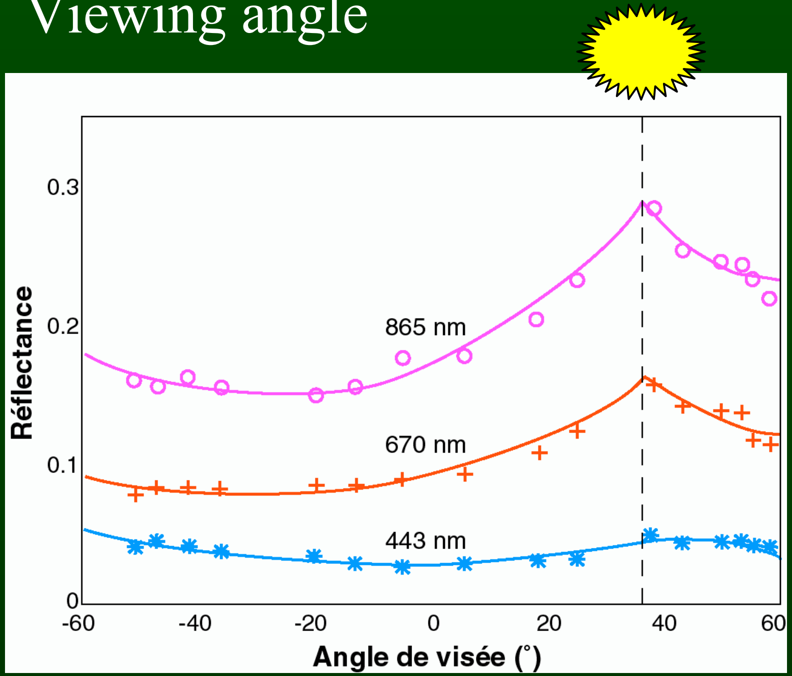
Wavelength



Sugar beet - Brooms Barn

AVIRIS, MODIS, MERIS

Viewing angle



Savannah - Niger - POLDER

POLDER, MISR

$$R = R(\lambda, \theta_s, \theta_v, \varphi_v)$$

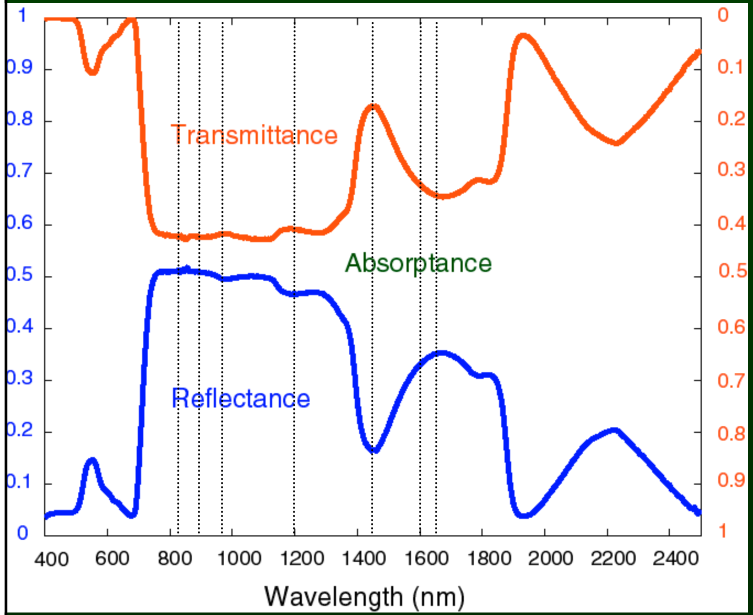
Question: How to estimate vegetation water content from measurements of reflectance?

Semi-empirical models

- Correlation between leaf water status and simple wavebands or combination of wavebands

$$C_w = f\left(\rho(\lambda_1),\ldots,\rho(\lambda_n)\right)$$

At the leaf level



$$EWT = \alpha\frac{\rho_{1650}}{\rho_{1430}} + \beta$$

Aoki *et al.* (1988)

$$RWC = f\left(\frac{\rho_{1600}}{\rho_{820}}\right) = f(MSI)$$

Ceccato *et al.* (2001)

$$EWT = \alpha\frac{\rho_{1200}}{\rho_{1430}} + \beta$$

Inoue *et al.* (1993)

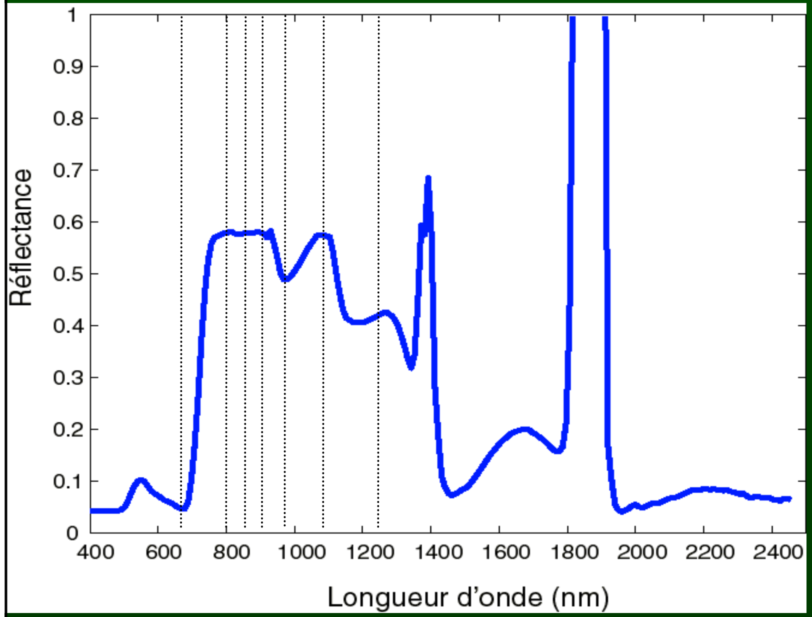
$$EWT = \alpha\frac{\rho_{970}}{\rho_{900}} + \beta = \alpha WI + \beta$$

Peñuelas *et al.* (1993)

$$RWC = LWCI = \frac{-\ln(1-(\rho_{820}-\rho_{1600}))}{-\ln(1-(\rho_{820}-\rho_{1600}^{FT}))}$$

Hunt *et al.* (1987, 1989)

At the canopy level



Relative Depth Index

$$RDI = 100 \times \frac{R_{1116} - R_{\min}}{R_{1116}}$$

$$with\ R_{\min} = \min\{R_{1120} \rightarrow R_{1250}\}$$

Rollin and Milton (1998)

Normalized Difference Water Index

$$NDWI = \frac{R_{860} - R_{1240}}{R_{860} + R_{1240}}$$

Gao (1996)

Water Band Index

$$WBI = \frac{R_{900}}{R_{970}}$$

Gamon *et al.* (1999)

Canopy Structure Index

$$CSI = 2sSR - sSR^2 + sWI^2$$

$$sSR = \frac{1}{20}\left(\frac{R_{800}}{R_{680}} - 1\right) and\ sWI = \frac{1}{0.8}\left(\frac{R_{900}}{R_{1180}} - 1\right)$$

Sims and Gamon (2003)

Modified Normalized Difference Water Index

$$mNDWI = \frac{R_{1070} - R_{1200}}{R_{1070} + R_{1200}}$$

Roberts *et al.* (2003)

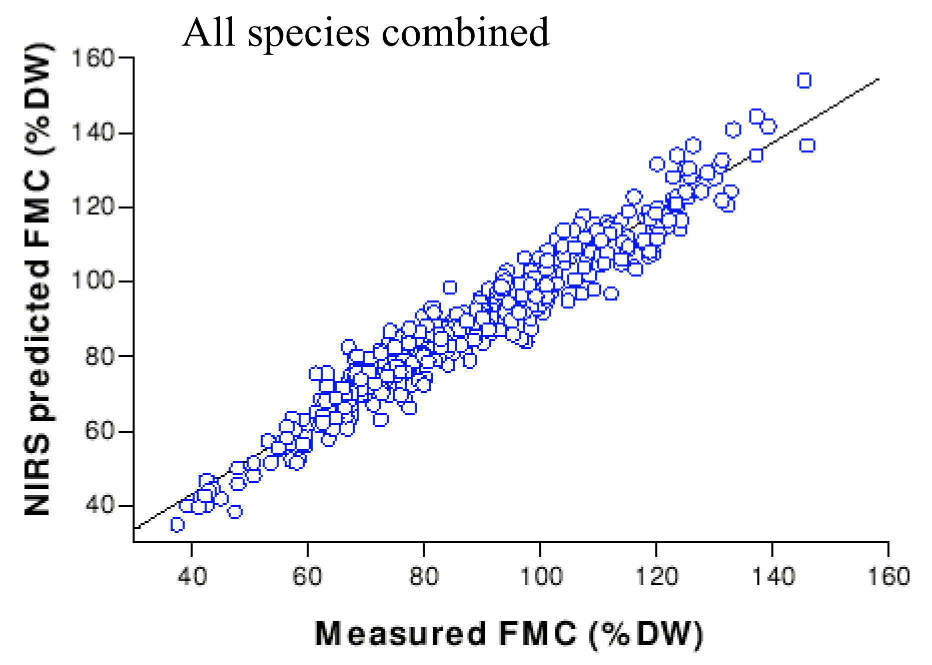
AVIRIS: Wallula, WA 970723

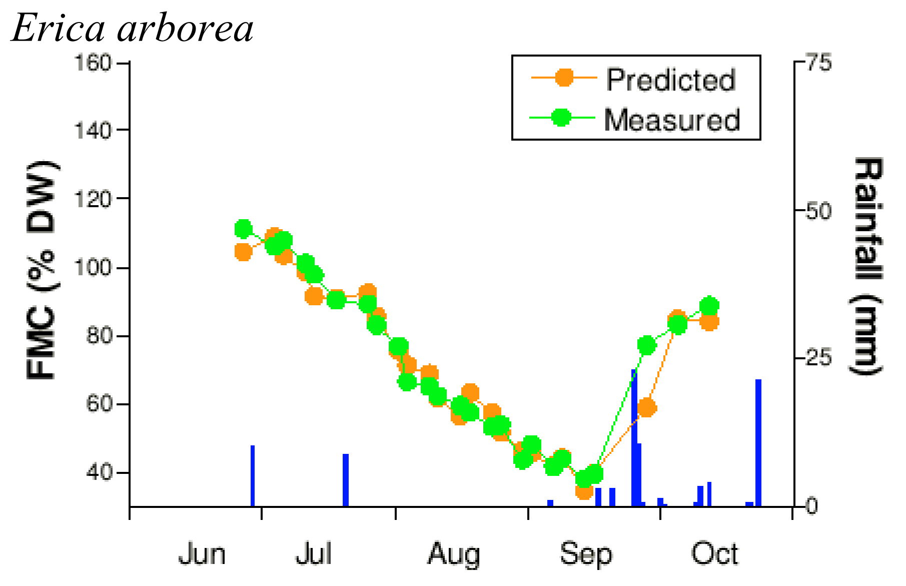
AVIRIS: Wallula, WA 970723 Leaf Water 1180

D.A. Roberts, K. Brown, R. Green, S. Ustin & T. Hinkley, 1989, 7th *Airborne Earth Science Workshop*, Pasadena (USA), pp. 335-344.

- Multiple stepwise regression analysis

$$C_w = \sum_{i=1}^{n} \alpha_i \, \rho(\lambda_i)$$

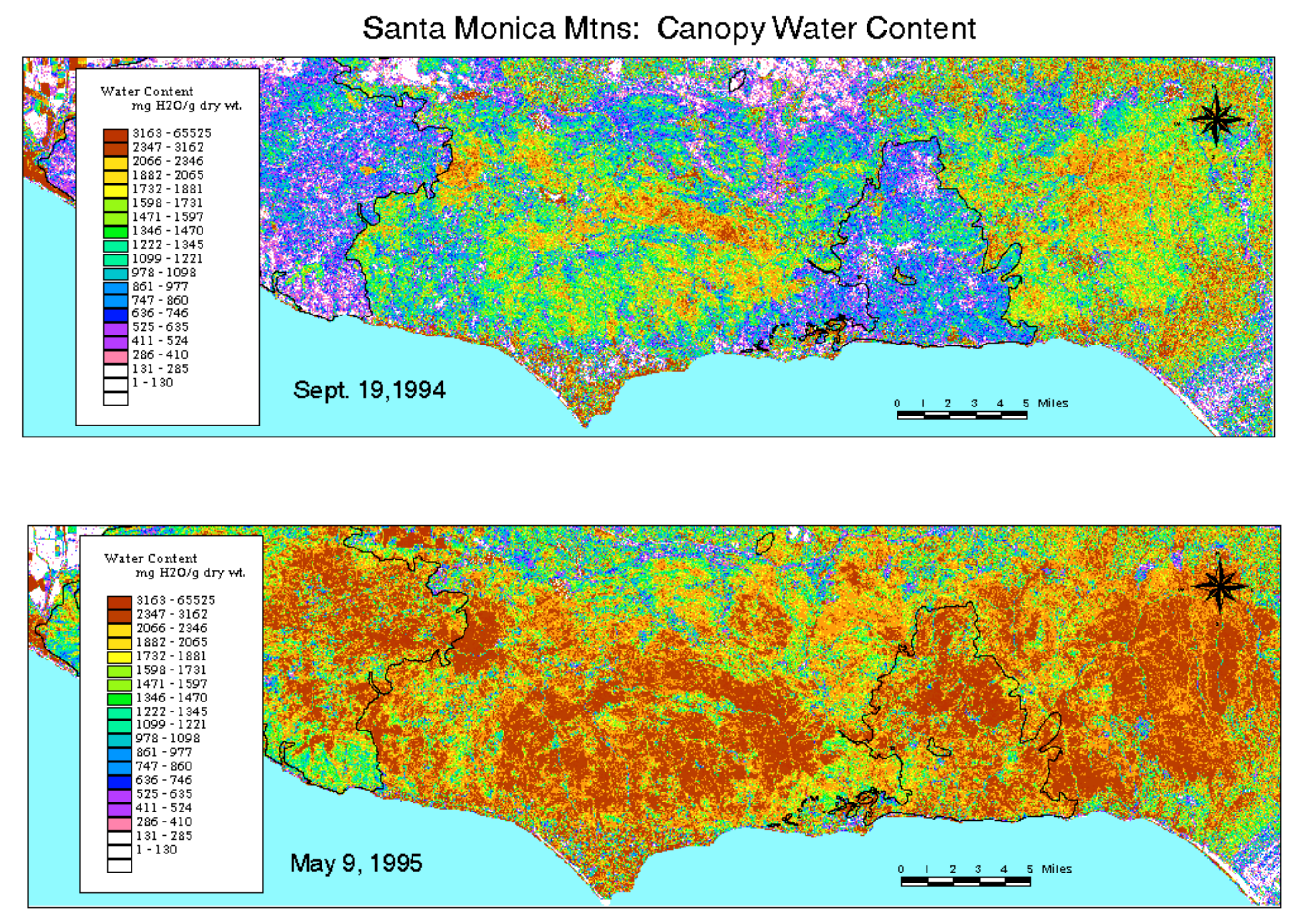




D. Gillon, F. Dauriac, M. Deshayes, J.C. Valette & C. Moro, 2002, *4th International Conference on Forest Fire Research*, Luso (Portugal), 13 p.

- Spectral mixture analysis

$$R(\lambda) = (a + b\,\lambda)\exp\left(-\sum_{i=1}^{n} k_i(\lambda) C_i\right)$$



Santa Monica Mtns: Canopy Water Content

Spectral fitting of liquid water absorption during atmospheric calibration procedure

S.L. Ustin, D.A. Roberts, J.E. Pinzón, S. Jacquemoud, M. Gardner, G. Scheer, C.M. Castañeda & A. Palacios-Orueta, 1998, *Remote Sens. Environ.*, 65:280-291.

Radiative transfer models

Why use models?

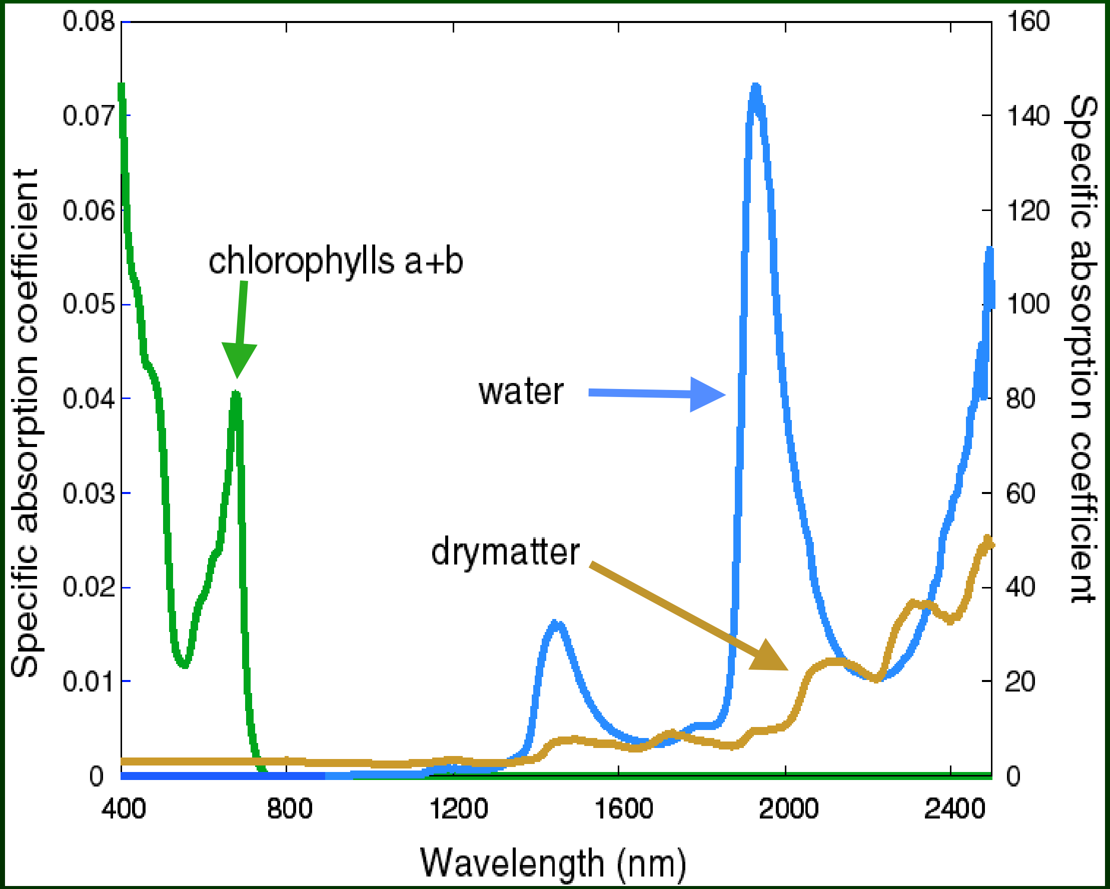
- Increase our understanding of how electromagnetic radiation interacts with the elements comprising terrestrial ecosystems → sensitivity analyses: direct mode
- Relate remote sensing observables to fundamental biophysical attributes → model optimization: inverse mode
- Understand the scaling properties of observable electromagnetic features and responses
- Develop correction techniques to handle the variable nature of sensor data

R. Myneni, 1995

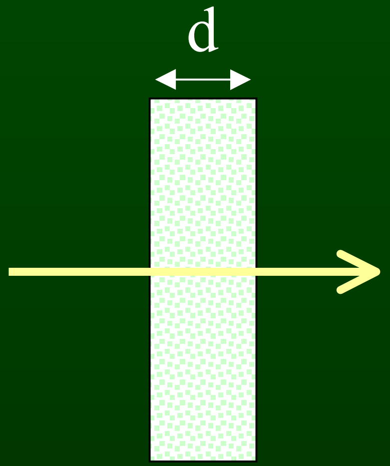
Leaf optical properties models

Plate models	PROSPECT	- leaf structure parameter - biochemical content	$\rho(\lambda)$, $\tau(\lambda)$, $\varphi(\lambda)$
N-flux models	K-M	- scattering coefficient - biochemical content	
Radiative transfer equation	LEAFMOD		$\rho(\lambda)$, $\tau(\lambda)$
Compact spherical particle models	LIBERTY	- cell diameter - leaf thickness - intercellular air spaces - biochemical content	
Stochastic models	LFMOD1, SLOP	- probabilities of scattering and absorption - biochemical content	$\rho(\lambda)$, $\tau(\lambda)$, $\varphi(\lambda)$
Ray tracing models	RAYTRAN, ABM	- description of the leaf internal structure in three dimensions - biochemical content	$\rho(\lambda,\theta)$, $\tau(\lambda,\theta)$

Specific absorption coefficient of constituent i: $k_i(\lambda)$



$$k(\lambda) = \Sigma\, k_i(\lambda) \times C_i$$

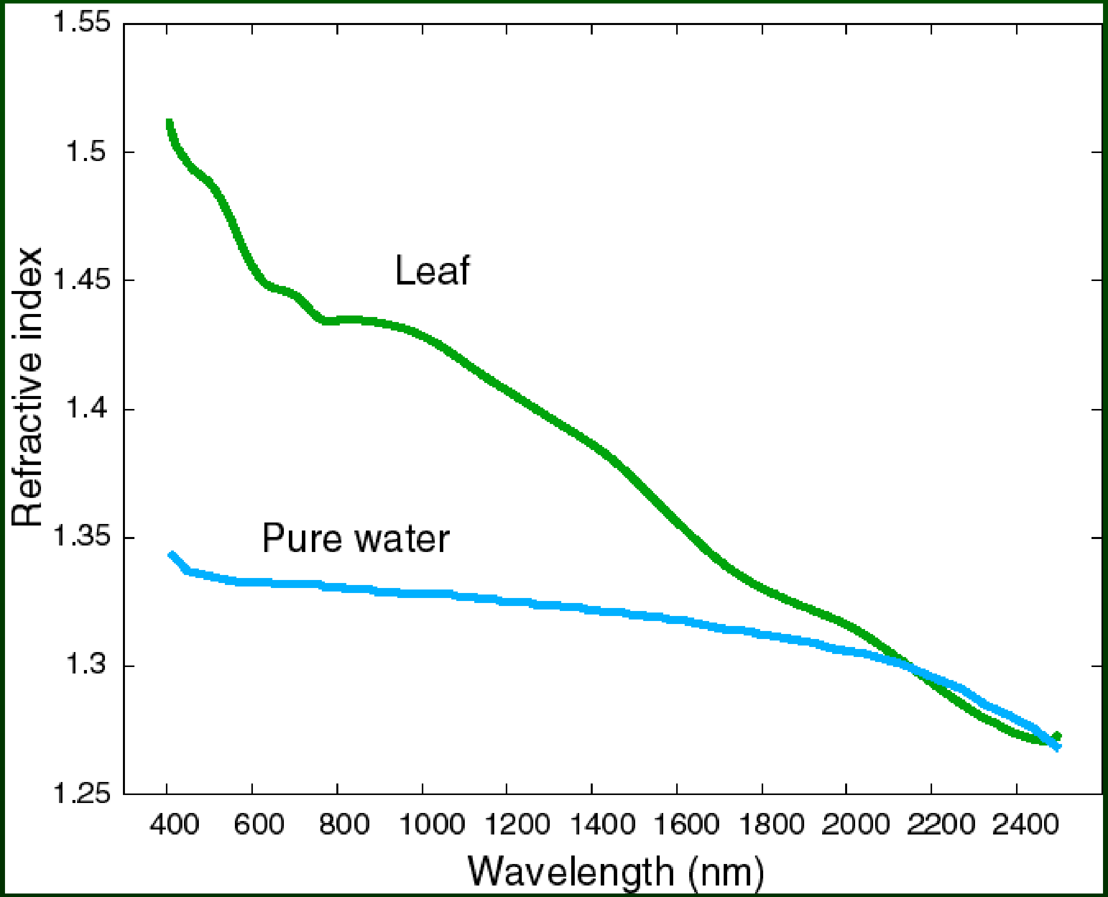


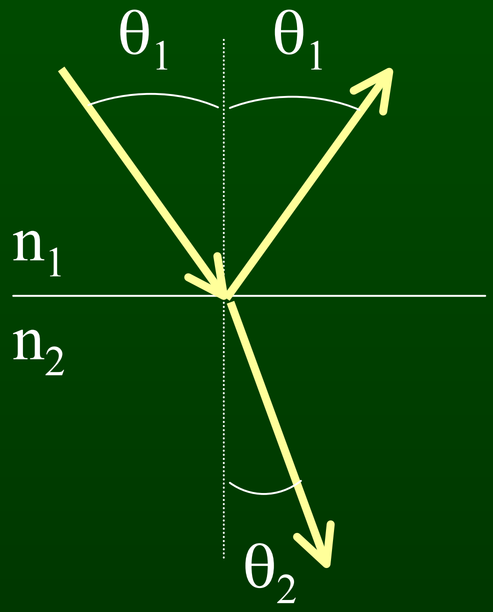
$$T(\lambda) = \exp(-k(\lambda) \times d)$$

S. Jacquemoud, S.L. Ustin, J. Verdebout, G. Schmuck, G. Andreoli & B. Hosgood, 1996, *Remote Sens. Environ.*, 56:194-202.

F. Baret & T. Fourty, 1997, *Agronomie*, 17:455-464.

Real refractive index of constituent i: $n_i(\lambda)$



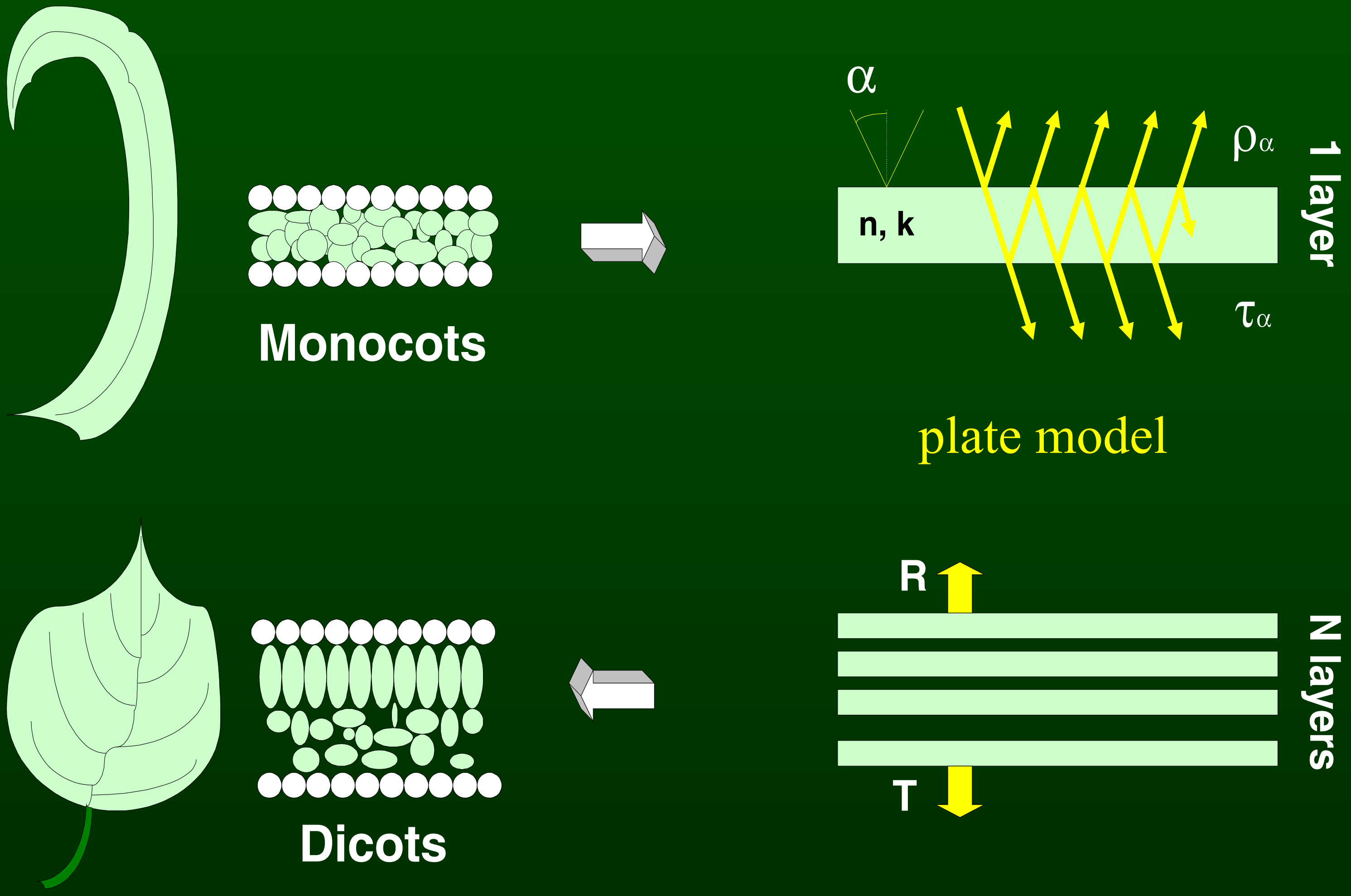


$$n_1 \times \sin\theta_1 = n_2 \times \sin\theta_2$$

K.F. Palmer & D. Williams, 1974, *J. Opt. Soc. Am.*, 64:1107-1110.

S. Jacquemoud & F. Baret, 1990, *Remote Sens. Environ.*, 34:75-91.

The PROSPECT model



Monocots

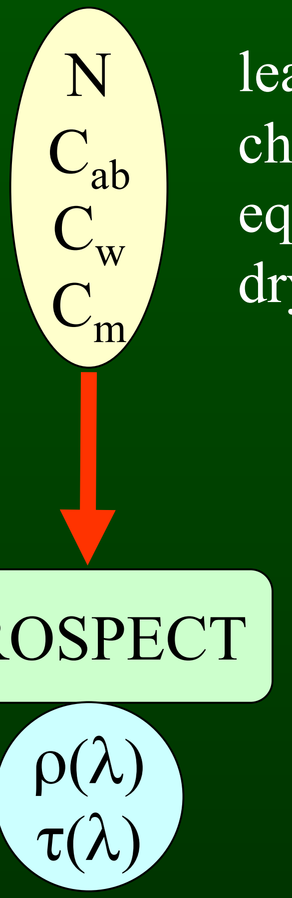
plate model

Dicots

N layers model

W.A. Allen, H.W. Gausman, A.J. Richardson & J.R. Thomas, 1969, *J. Opt. Soc. Am.*, 59:1376-1379.

G.G. Stokes, 1862, *Proc. Roy. Soc. Lond.*, 11:545-556.



N

C_{ab}

C_w

C_m

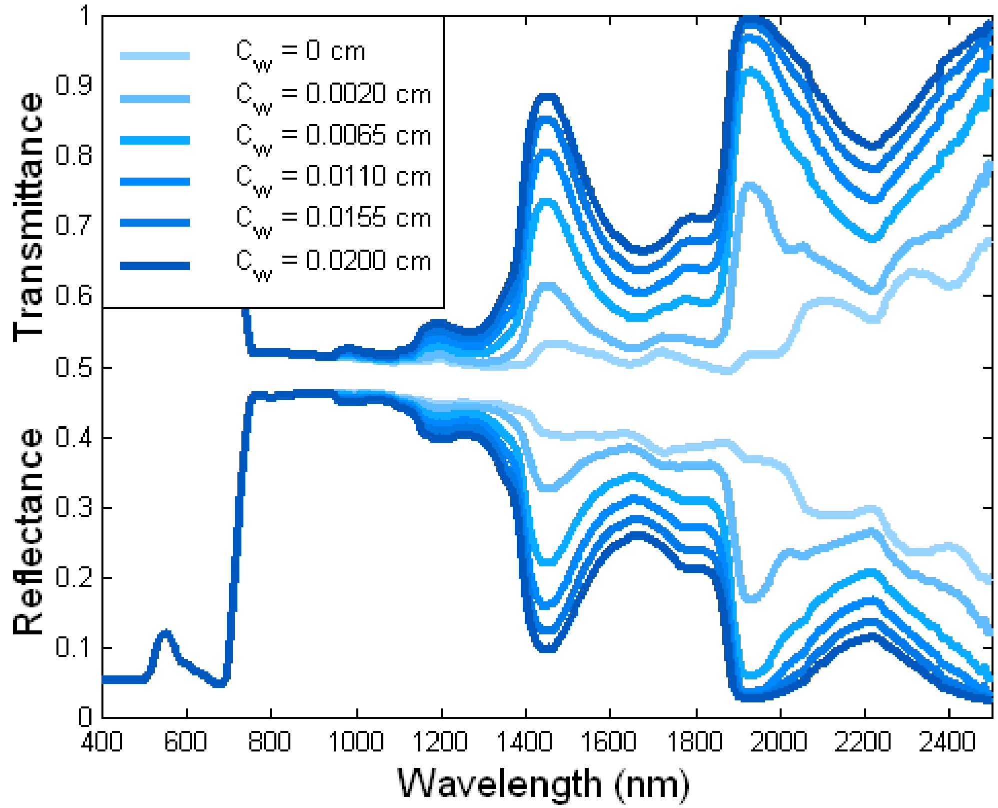
PROSPECT

$\rho(\lambda)$

$\tau(\lambda)$

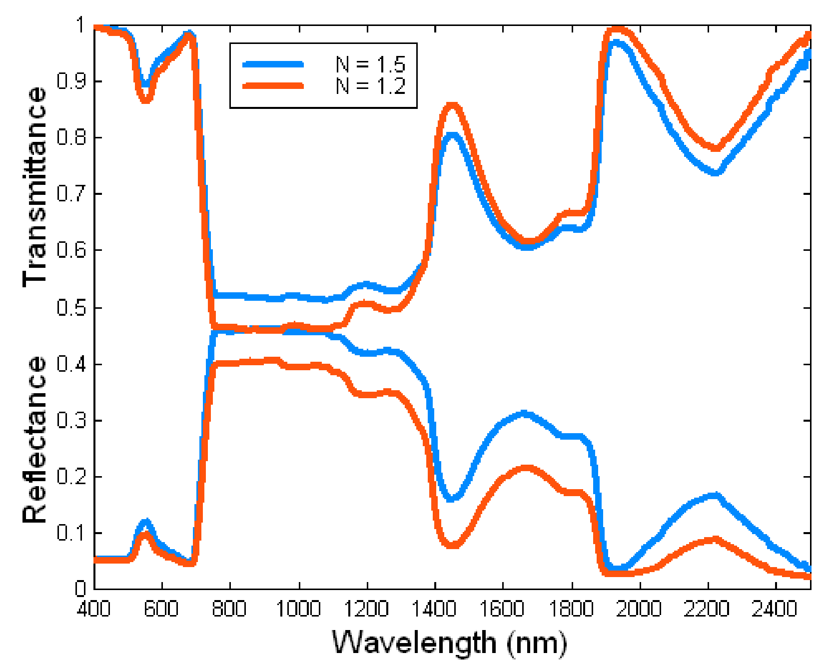
leaf structure parameter
chlorophyll *a*+*b* concentration ($\mu g.cm^{-2}$)
equivalent water thickness (cm)
dry matter content ($g.cm^{-2}$)

$N = 1.5$, $C_{ab} = 50\ \mu g.cm^{-2}$, $C_m = 0.005\ g.cm^{-2}$

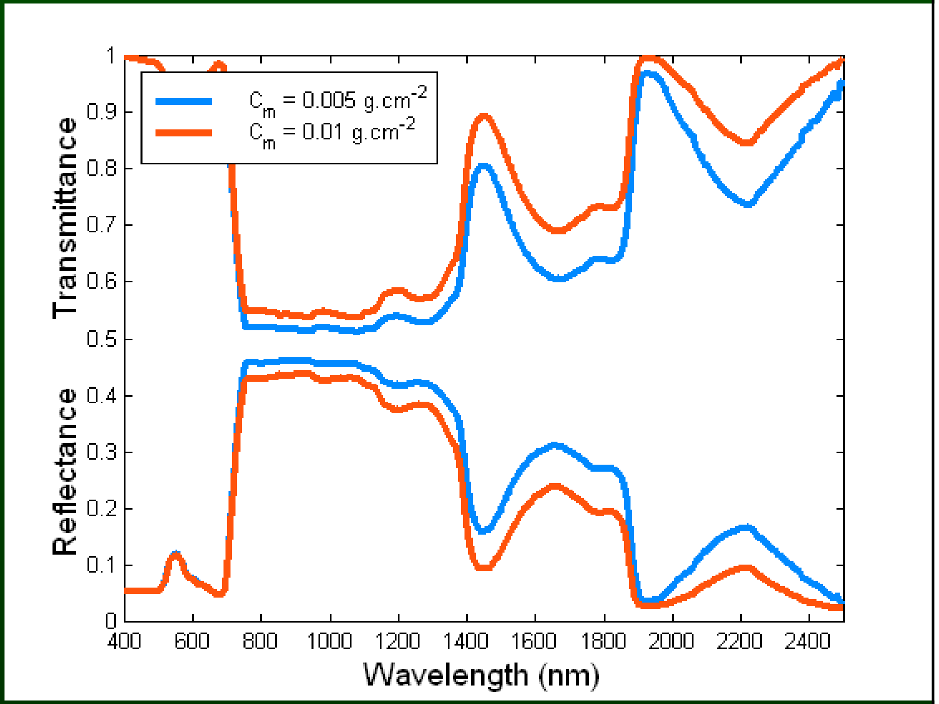


→ **Direct mode**

C_{ab} = 50 µg.cm^{-2}, C_w = 0.0110 cm, C_m = 0.005 g.cm^{-2}



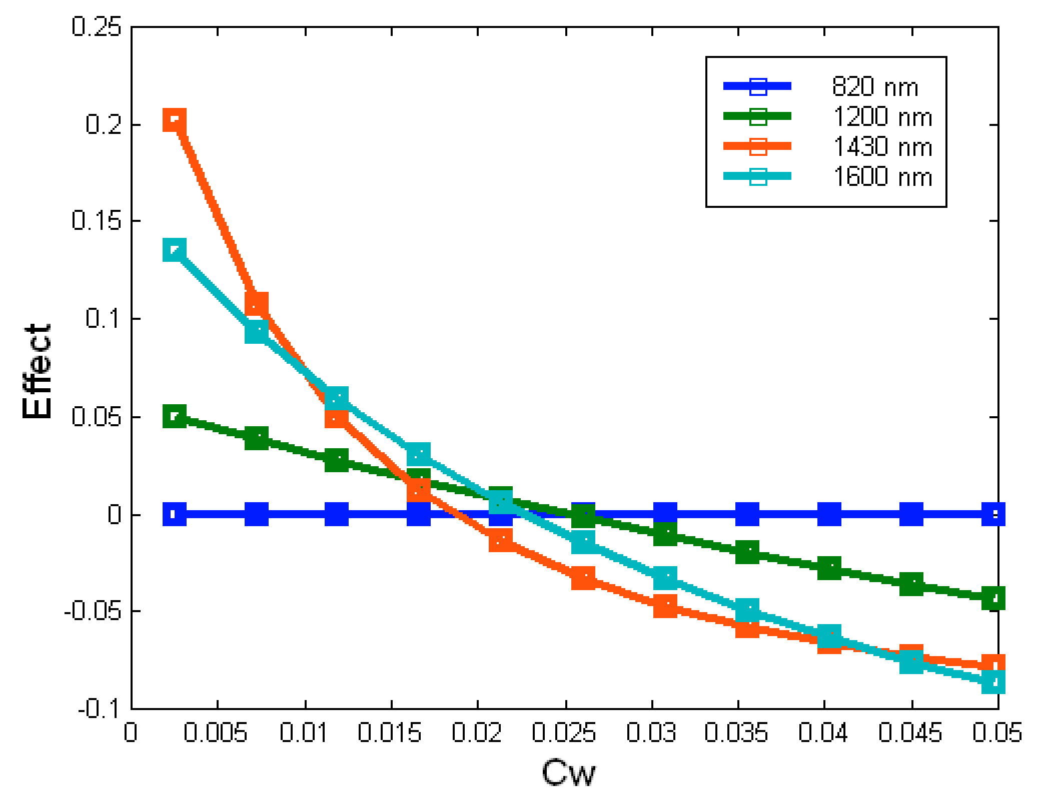
N = 1.5, C_{ab} = 50 µg.cm^{-2}, C_w = 0.0110 cm



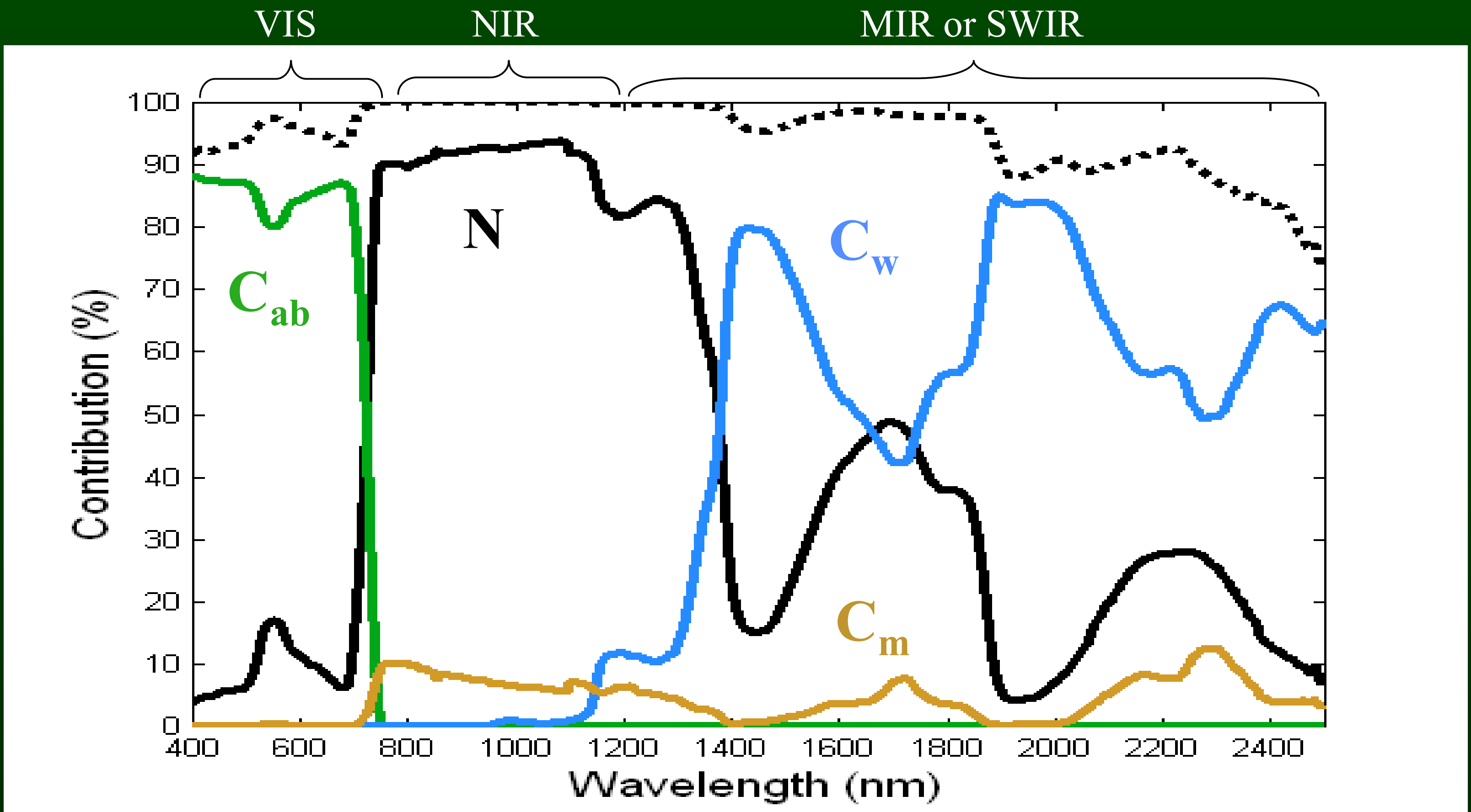
Spectral sensitivity analysis of PROSPECT with the design of numerical experiments method → matrix model

$$[\rho(\lambda),\tau(\lambda)] = N + C_{ab} + C_w + C_m + N\,C_{ab} + N\,C_w + N\,C_m + C_{ab}\,C_w + C_{ab}\,C_m + C_w\,C_m$$

Effect of C_w on leaf reflectance computed with PROSPECT



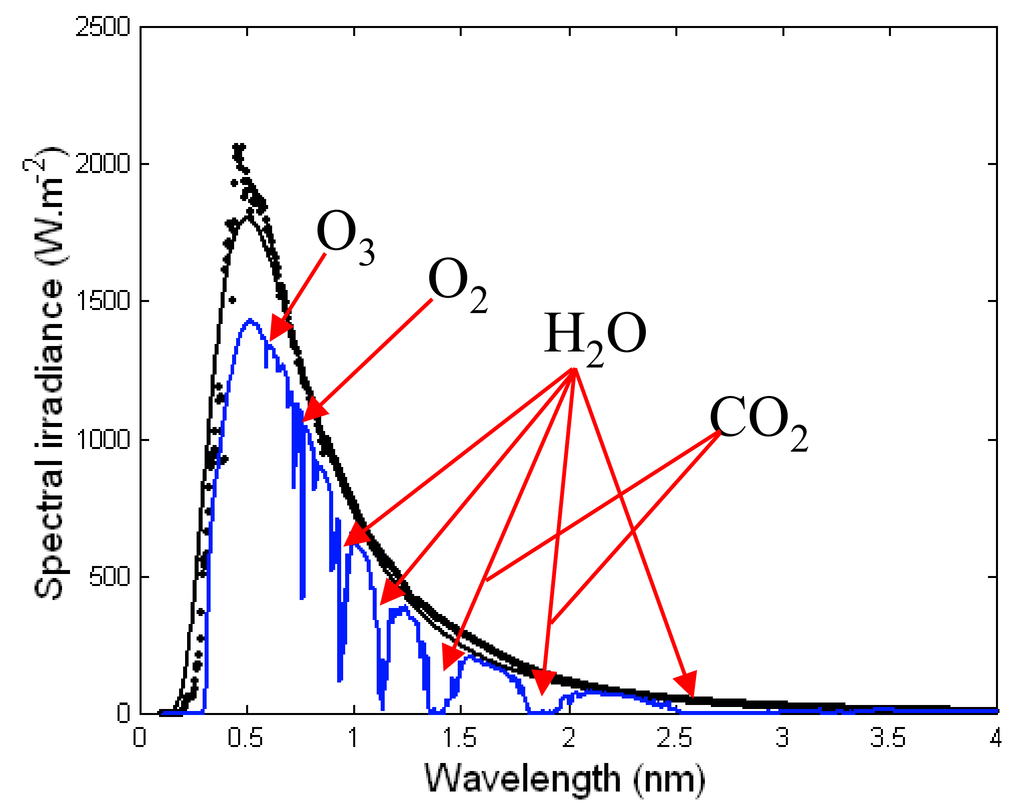
Contribution of N, C_{ab}, C_w, and C_m on leaf reflectance computed with PROSPECT



Canopy reflectance models

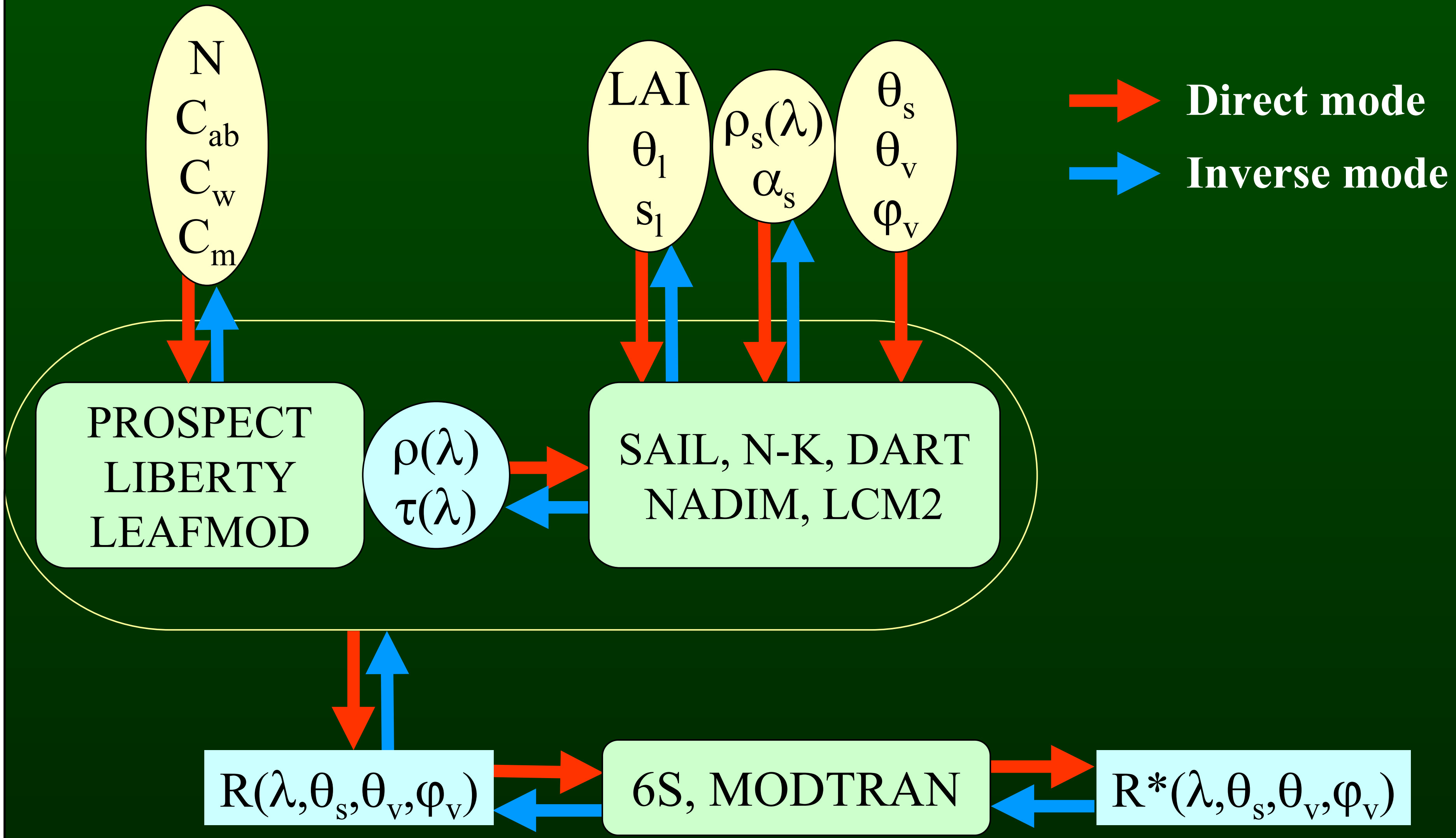
Parametric models	LiSK, RPV	- albedo - shape of the radiation field	$R(\lambda,\theta)$
N-flux models	LAM, SAIL, K-M	- leaf optical properties - canopy architecture - soil optical properties	$R(\lambda,\theta)$, $F(\lambda)$
Radiative transfer equation	LCM2, NADIM, N-K		$R(\lambda,\theta)$
Geometrical models	SLS	- leaf optical properties - description of the canopy architecture in three dimensions - soil optical properties	
Hybrid models	DART, GORT		
Radiosity and ray tracing models	RAYTRAN, FLIGHT, SPRINT, RGM		

Scaling-up to the satellite level



Radiative transfer models	5S, 6S, LOWTRAN, MODTRAN	- canopy reflectance - horizontal visibility - model of atmosphere - aerosol model	$R^*(\lambda,\theta)$

Use of radiative transfer models to simulate plant canopy spectral and bidirectional reflectance



N
C_{ab}
C_w
C_m

LAI
θ_l
s_l

$\rho_s(\lambda)$
α_s

θ_s
θ_v
φ_v

→ Direct mode

→ Inverse mode

PROSPECT
LIBERTY
LEAFMOD

$\rho(\lambda)$
$\tau(\lambda)$

SAIL, N-K, DART
NADIM, LCM2

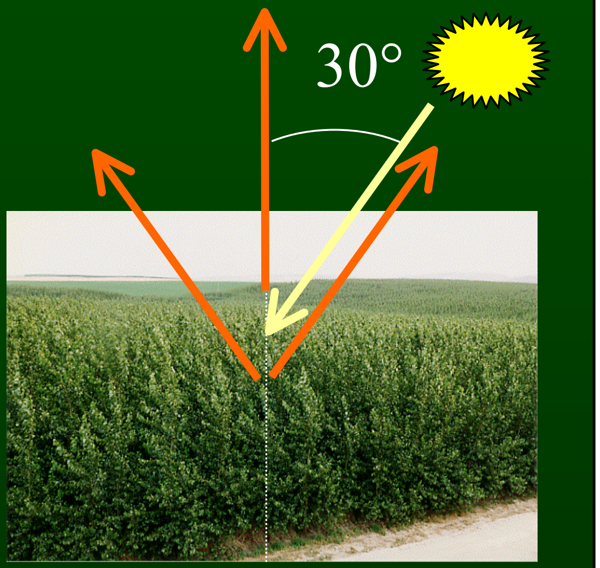
$R(\lambda,\theta_s,\theta_v,\varphi_v)$

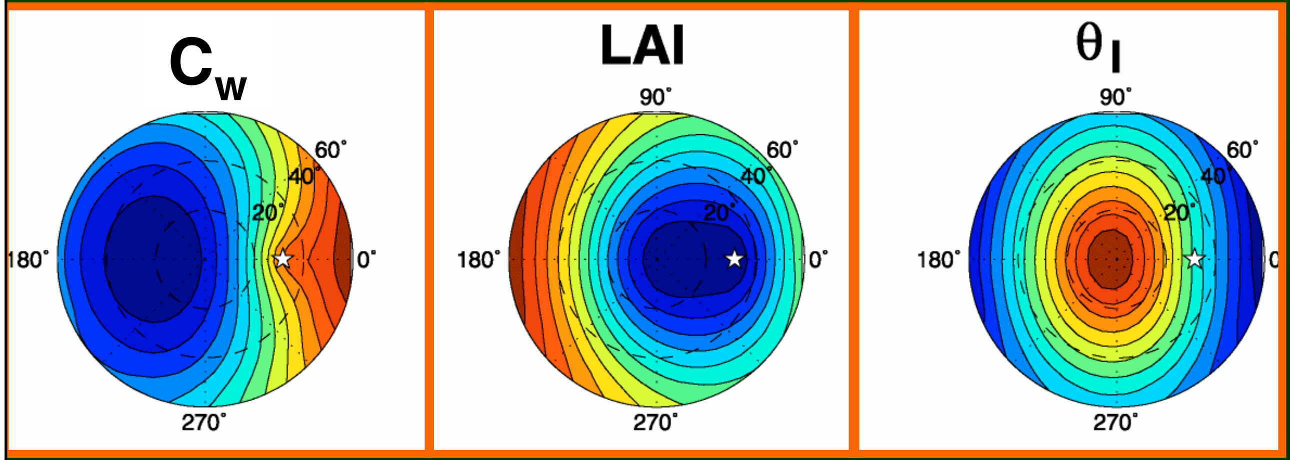
6S, MODTRAN

$R^*(\lambda,\theta_s,\theta_v,\varphi_v)$

Bidirectional sensitivity of PROSPECT+SAIL (PROSAIL) with the design of numerical experiments method:

- Sun zenith angle: $\theta_s = 30°$
- canopy observed under several viewing angles θ_v





Equivalent water thickness C_w

Leaf area index LAI

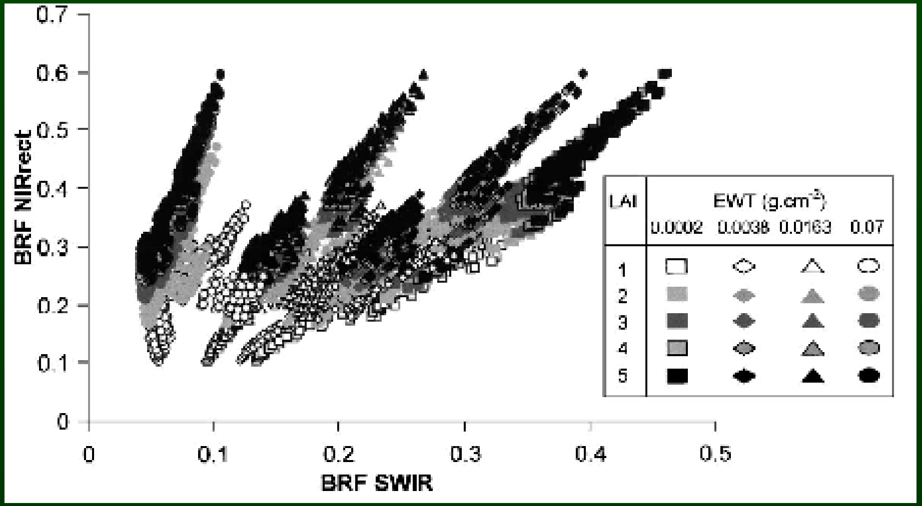
Leaf inclination angle θ_l

C. Bacour, 2001, *Contribution à la détermination des paramètres biophysiques des couverts végétaux par inversion de modèle de réflectance,* PhD Thesis, 206 p.

C. Bacour, S. Jacquemoud, Y. Tourbier, M. Dechambre & J.P. Frangi, 2002, *Remote Sens. Environ.*, 79:72-83.

Designing spectral indices to estimate vegetation water content: The Global Vegetation Moisture Index (GVMI)

(1) rectification of the NIR band to avoid atmospheric and angular effects
(2) combination with the SWIR band to generate an optimal index formulae



Simulations with
PROSPECT + NADIM + 6S

$$GVMI = \frac{(NIR_{rect} + 0.1) - (SWIR + 0.02)}{(NIR_{rect} + 0.1) + (SWIR + 0.02)}$$

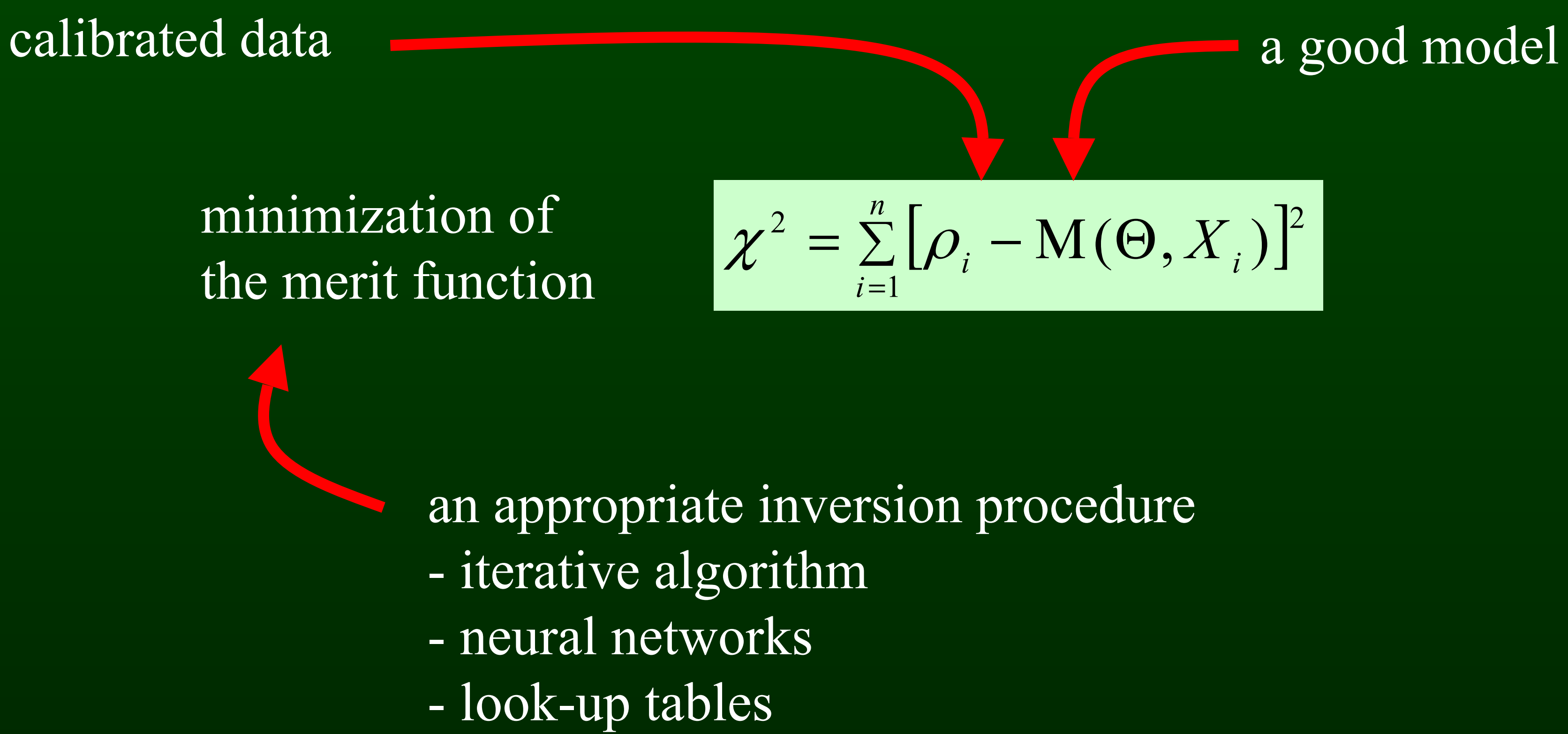
$$GVMI = 1.53 - \frac{1.4}{1 + 0.000517 \times EWT_{canopy}} - 0.000099 \times EWT_{canopy}$$

P. Ceccato, N. Gobron, S. Flasse, B. Pinty & S. Tarantola, 2002, *Remote Sens. Environ.*, 82:188-197.

Inversion of canopy reflectance models

The inversion procedure consists in retrieving the unknown parameter vector Θ by minimizing the non-linear least-squares function χ^2:

A successful inversion is the conjunction of three factors:



calibrated data

a good model

minimization of
the merit function

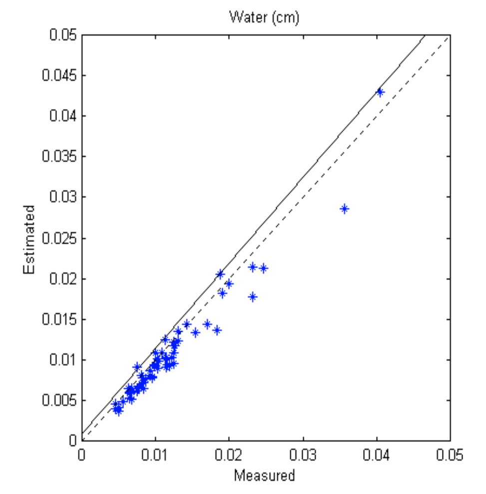
$$\chi^2 = \sum_{i=1}^{n} \left[\rho_i - \mathrm{M}(\Theta, X_i)\right]^2$$

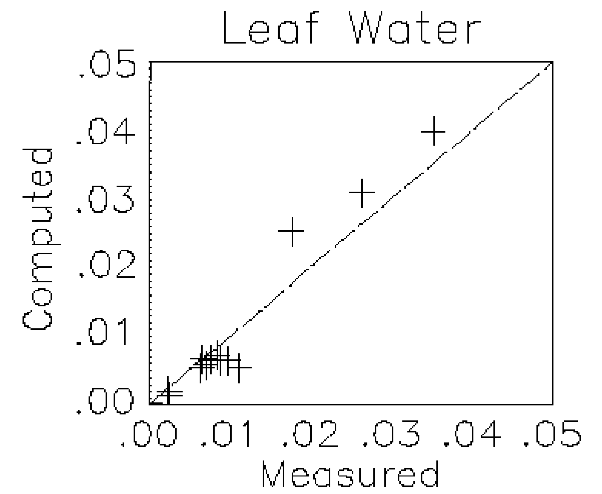
an appropriate inversion procedure
- iterative algorithm
- neural networks
- look-up tables

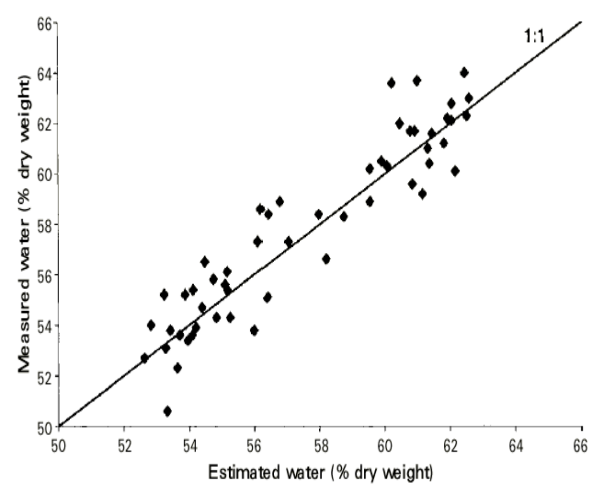
- Retrieval of water content at the leaf level

$$\chi^2 = \sum_{i=1}^{n} \{\rho_i - \rho_{\mathrm{mod}}(\Theta,\lambda)\}^2 + \{\tau_i - \tau_{\mathrm{mod}}(\Theta,\lambda)\}^2$$

		Water	R^2	**RMSE**
PROSPECT	Baret and Fourty (1997)	*EWT*	×	0.0025 cm
	Jacquemoud *et al.* (2000)		0.95	0.0018 cm
	Newnham and Burt (2001)		0.93	×
LIBERTY	Dawson et al. (1998)	*FMC*	0.86	1.3

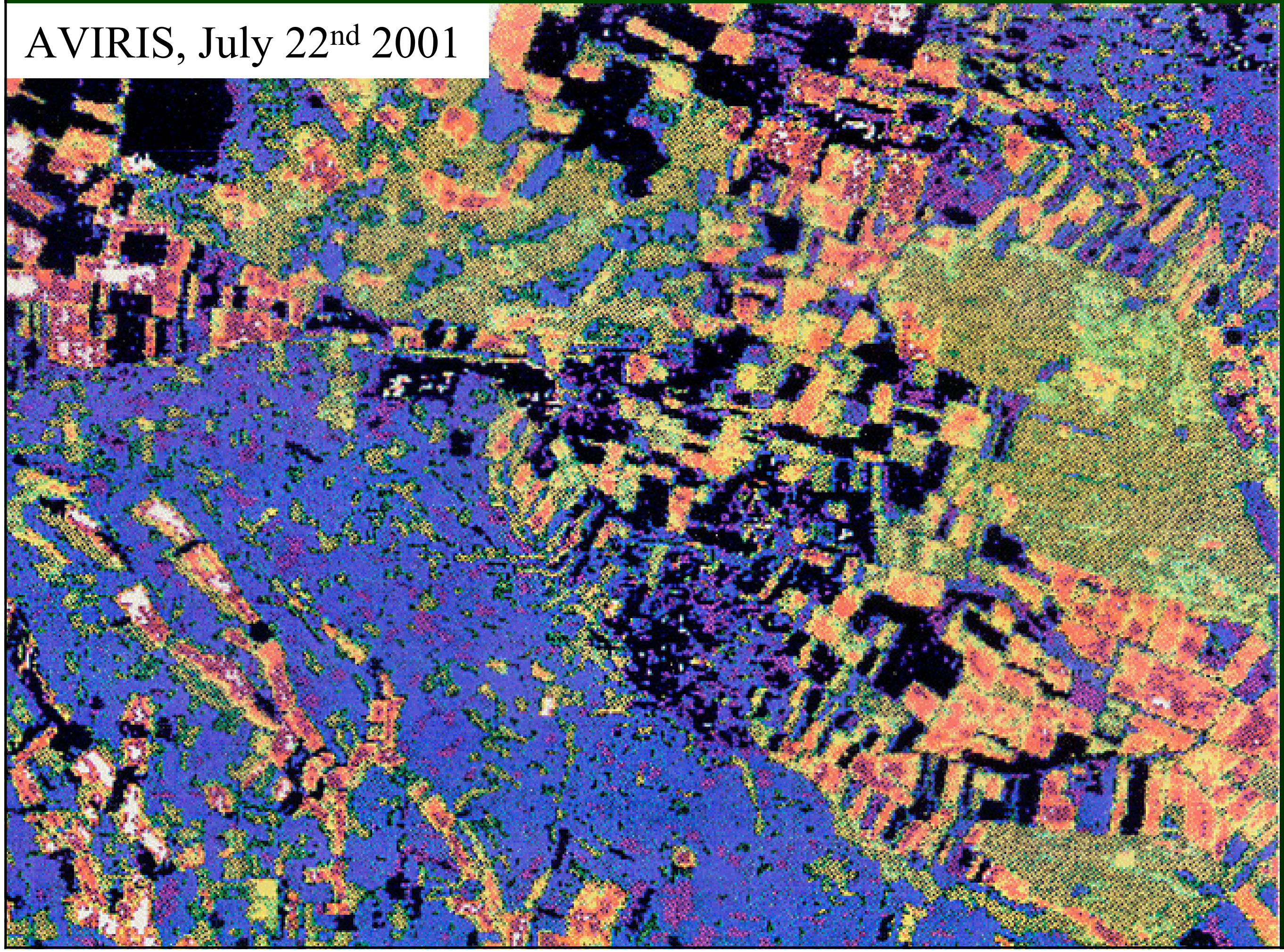






- Retrieval of water content at the canopy level

$$\chi^2 = \sum_{i=1}^{n} \left\{ R_i - R_{\mathrm{mod}}(\Theta, \lambda) \right\}^2$$



AVIRIS, July 22nd 2001

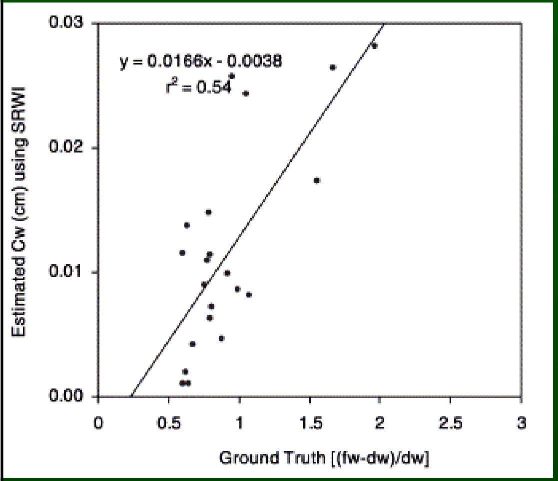
Step 1

spectral unmixing

Step 2

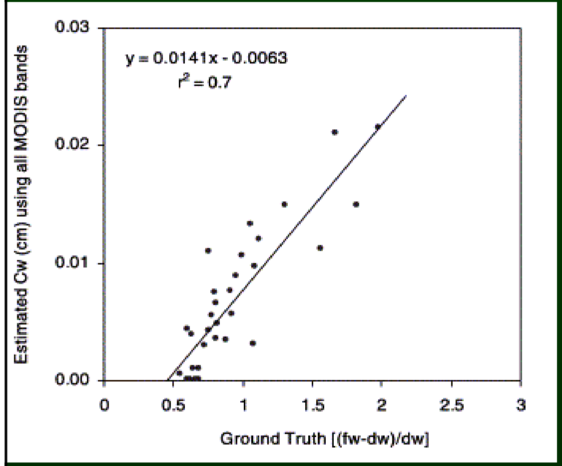
inversion of the K-M model on the 1.55-1.75 µm region

G. Schmuck, J. Verdebout, S.L. Ustin, A.J. Sieber & S. Jacquemoud, 1993, *25th International Symposium on Remote Sensing and Global Environmental Change*, Graz (Austria), pp. 273-281.

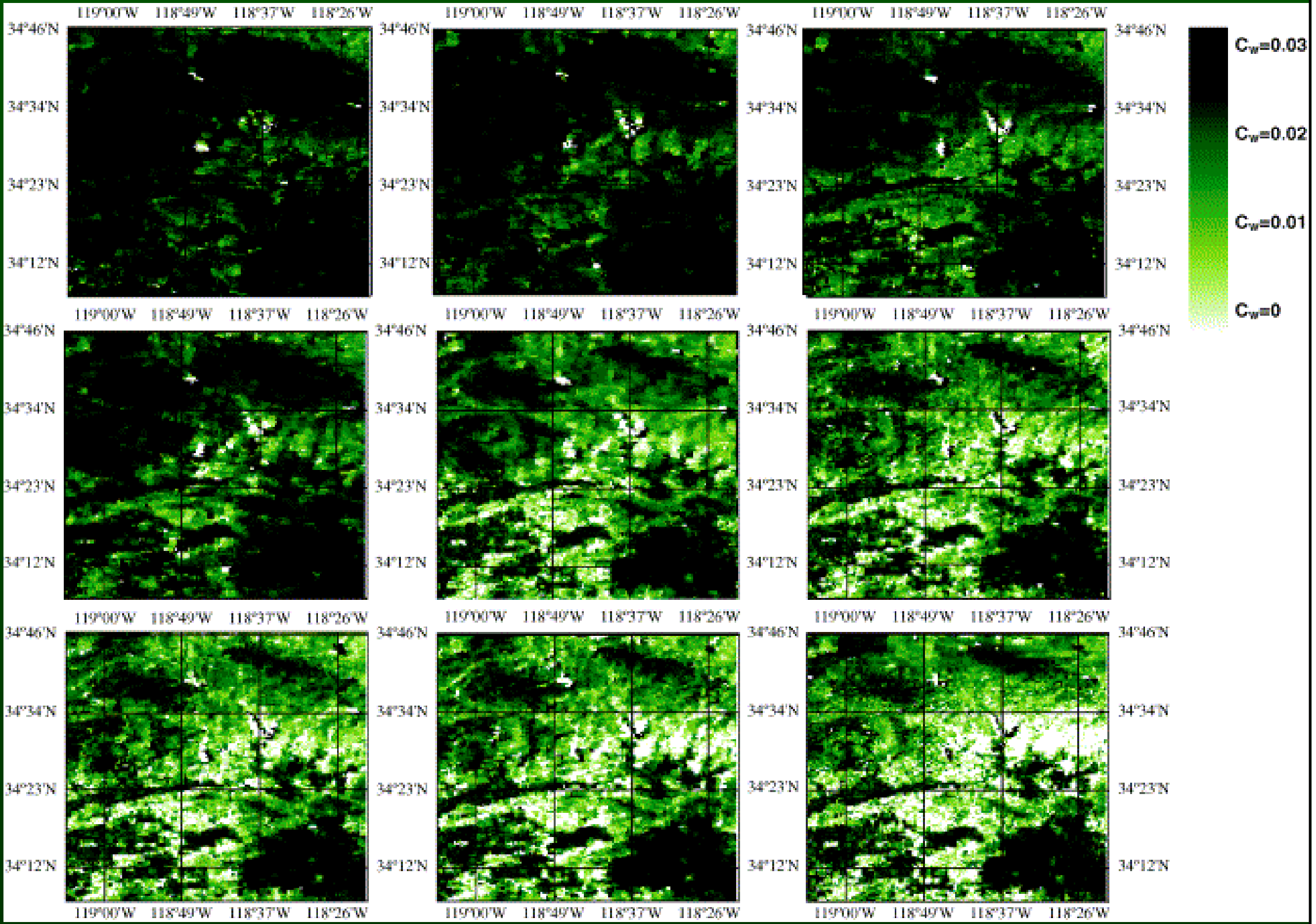


Simple Ratio Water Index

$$SRWI = \frac{R_{860}}{R_{1240}}$$



Inversion of
PROSPECT+SAILH



Time series of MODIS-estimated leaf C_w in the study region of chaparral vegetation used for ground truth data collection for the period June–September 2000 (Julian days 161, 169, 185, 201, 233, 241, 249, 265, and 273).

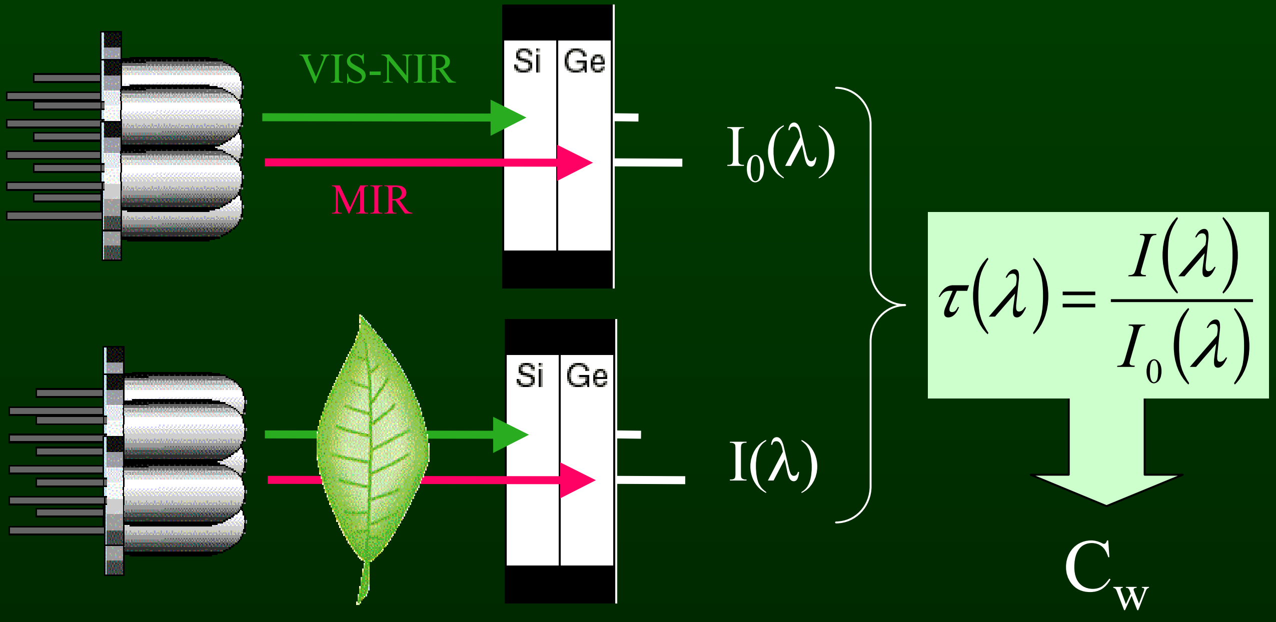
P.J. Zarco-Tejada, C.A. Rueda & S.L. Ustin, 2003, *Remote Sens. Environ.*, 85:109-124.

CONCLUSION

- The use of radiative transfer models to estimate vegetation moisture content is still in its infancy

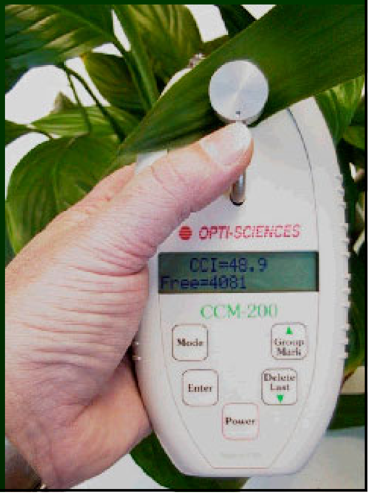
- Operational mapping will require more theoretical and field work:

- at the leaf level
- at the canopy level → inversion procedures, validation campaigns



$$\tau(\lambda) = \frac{I(\lambda)}{I_0(\lambda)}$$

C_w



- The use of other canopy biophysical characteristics might be useful to assess fire risk → canopy architecture, brown pigments, etc.
- The spectral and bidirectional properties of burnt areas are still unknown → laboratory measurements

Unburnt area

Moderately-burnt area

Severely-burnt area

The modeling of these properties is emerging → fitting of parametric models (Lajas *et al.*, 2001; Roy et al., 2003)

Food and Agriculture Organization, 2001, *Global Forest Fire Assessment 1990-2000*. Forest Resources Assessment Programme, 495 p.