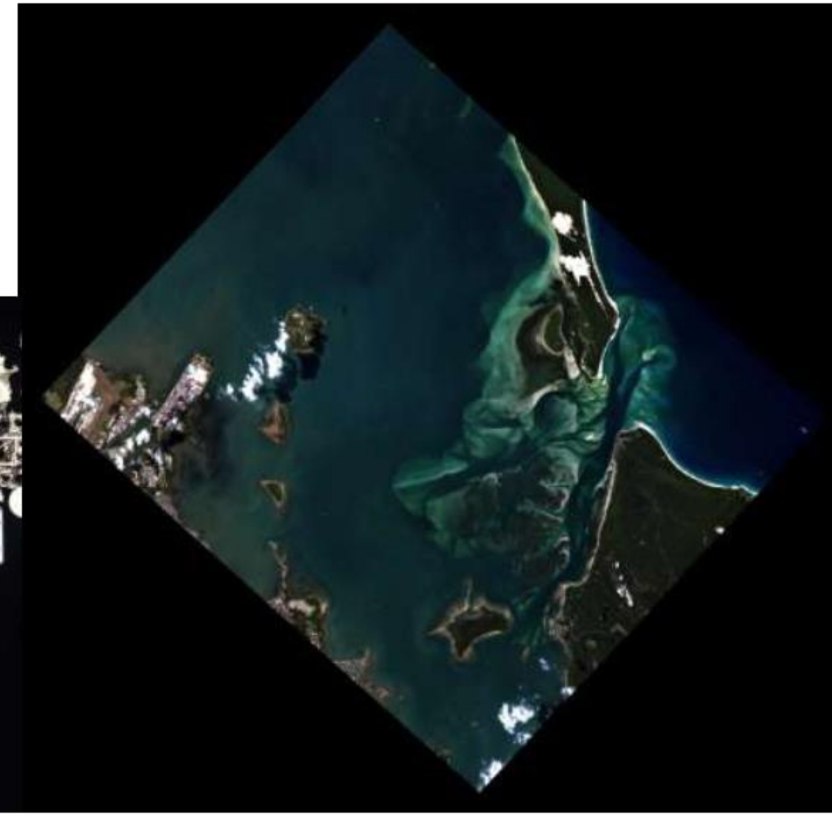

GEO 418 – „Hyperspectral Earth Observation“

Martin.Bachmann@dlr.de

Spectral Signatures

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Spectral Signatures of

- Vegetation
- Soil
- Minerals
- Water & Snow

Small recap…

Sonne

- Solare Ausstrahlung
- Sonnenatmosphäre, Sonnenfleckenzyklen
- Solarkonstante über der Erdatmosphäre

↓

Erdatmosphäre

- Absorption
- Transmission
- Reflektion / Streuung
- Weglänge, Sonnenstand
- Variable Zusammensetzung der Atmosphäre

I

↓

Erdoberfläche

- Absorption
- Transmission
- Reflektion
- Emission
- Topographie & weitere Effekte

II

↓

Erdatmosphäre

- Dto.
- Path Radiance

↓

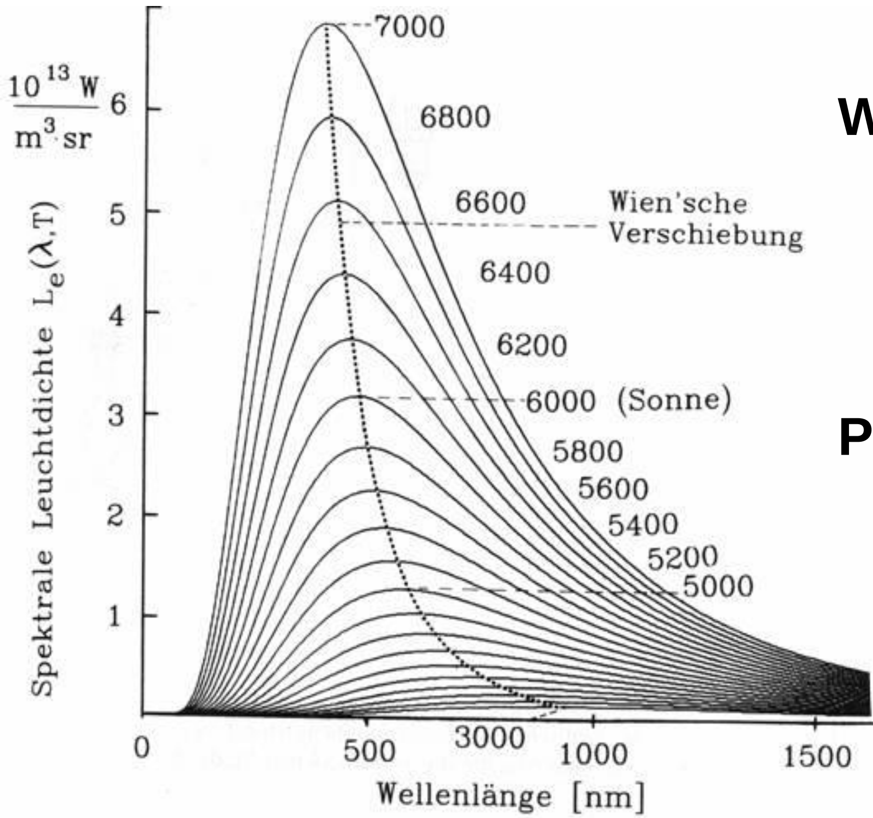
Sensor

- Plattform-Geometrie
- Sensor-Response & Sampling

III

Planck: Emittance M = f (λ, T)
with T: temperature λ: wavelengths

Boltzmann: $M_{blackbody} = \sigma \; T^4$ [W m^{-2}]
with $\sigma = 5.67 * 10^{-8}$ W m^{-2} K^{-1}



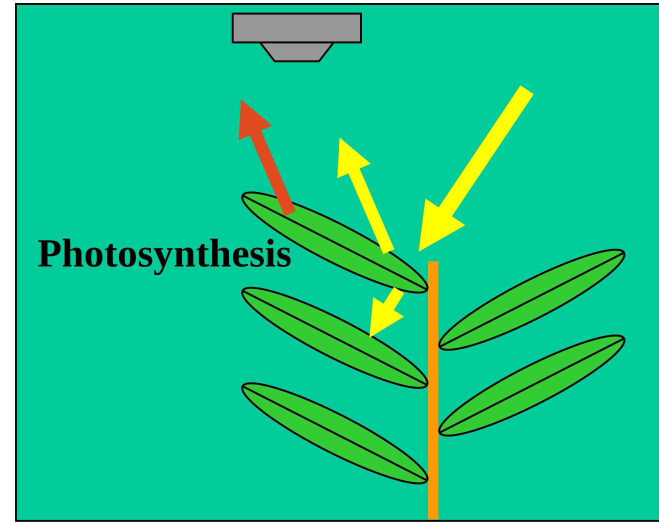
Wien's displacement law: $\lambda_{max} = 2898 \; / \; T$
The higher the temperature (T)
the smaller the wavelengths (λ_{max})
of maximum energy release

Photon energy: q = h / λ
h: Planck constant $6.63 * 10^{-34}$ [J s]

=> lower energy per photon with
increasing wavelengths

Energy per photon:
green 0.55 µm ➔ $3.61 * 10^{-19}$ J
TIR 12 µm ➔ $1.66 * 10^{-20}$ J
➔ 22 times the energy !

Energy balance relationship:



- $E_{\text{emitted by sun}} = E_{\text{reflected}} + E_{\text{transmitted}} + E_{\text{absorbed}}$

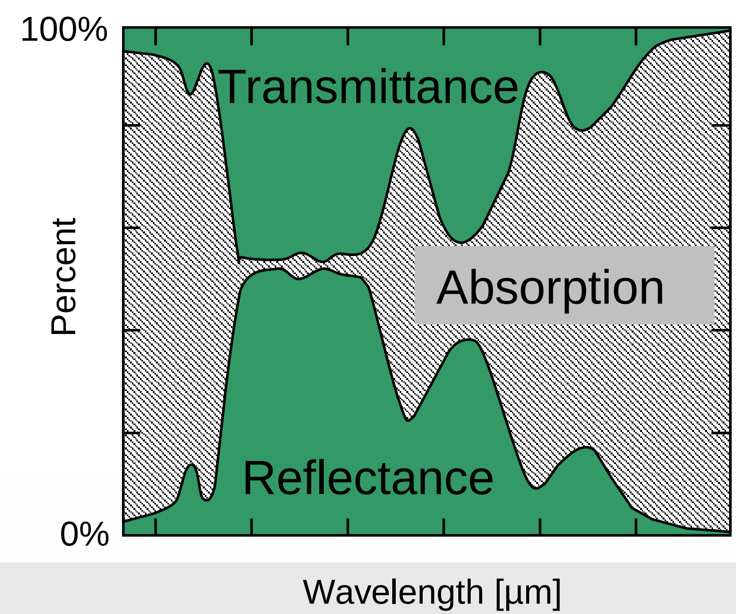
  E… Incident Energy [W]

- $1 = E_r / E_i + E_t / E_i + E_a / E_i$
- $1 = R + T + A$

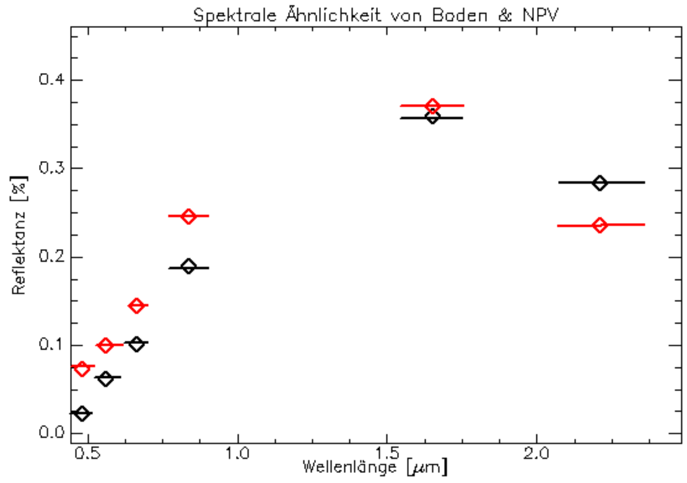
  …Reflection-coefficient + Transmission-coefficient + Absorption-coefficient

⇒ **Material property, independent of incomig radiant energy!**

… and now as a function of wavelength:



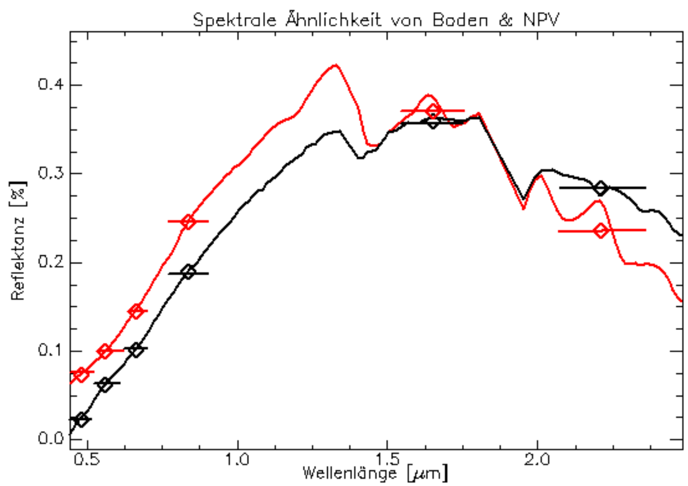
Information retrieval – spectral identification



Spectral signatures

Landsat TM
6 bands in VNIR & SWIR

Information retrieval – spectral identification

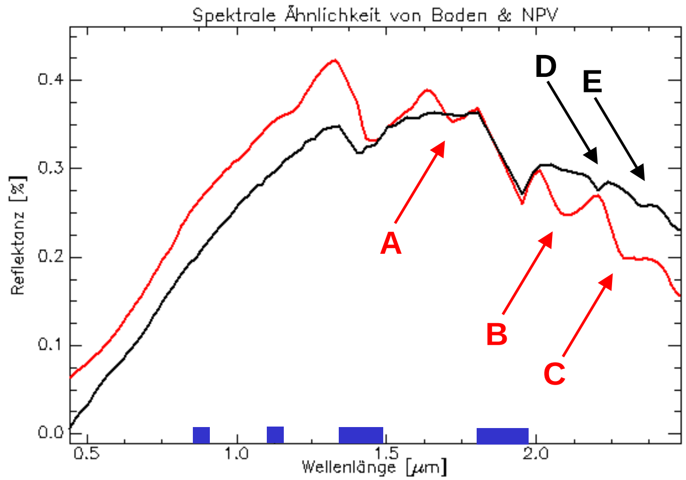


Spectral signatures

Landsat TM
6 bands in VNIR & SWIR

HyMAP
126 bands in VNIR & SWIR

Information retrieval – spectral identification



Absorption features of

A: Xylan & Cellulose
B: Lignin & Cellulose
C: Cellulose

} Vegetation without Chlorophyll ⇒ NPV

▬ : Water-Absorption

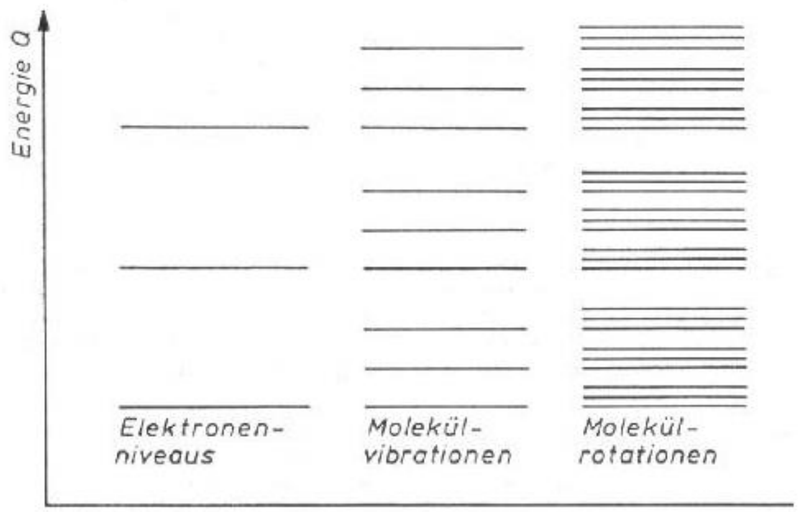
D: Clay
E: Carbonates

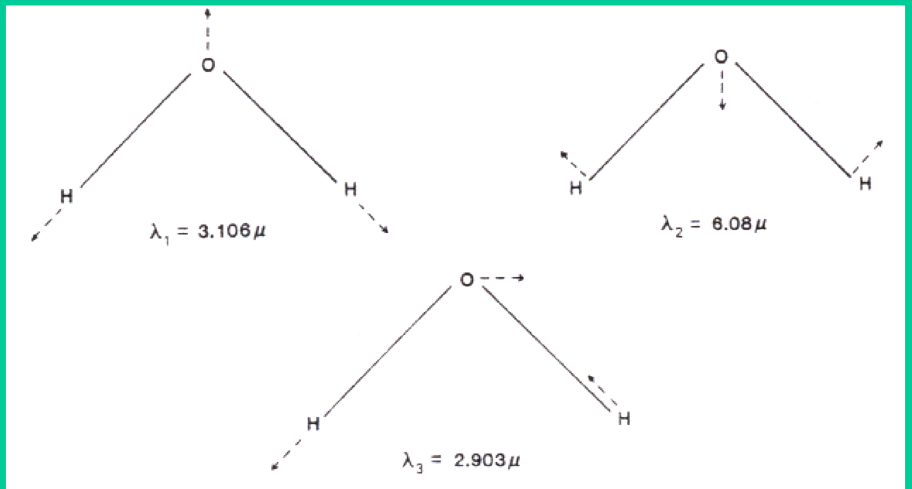
} Soil

Spectral signatures

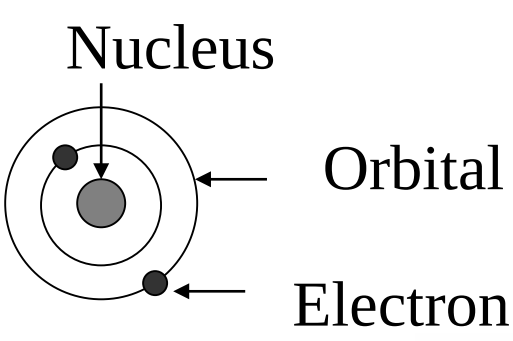
HyMAP
126 bands in VNIR & SWIR

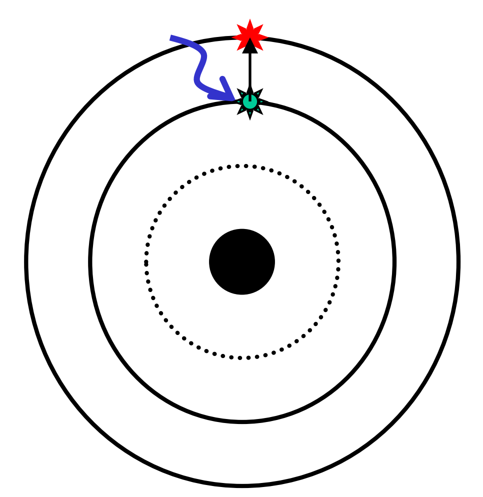
Absorption processes

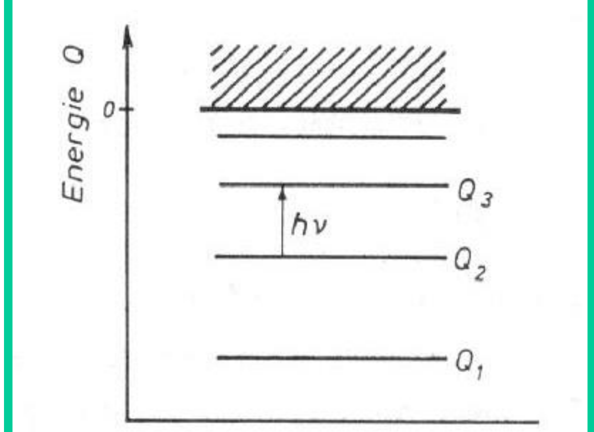




Molecular vibrations & - rotations







Electron transfer

Vegetation

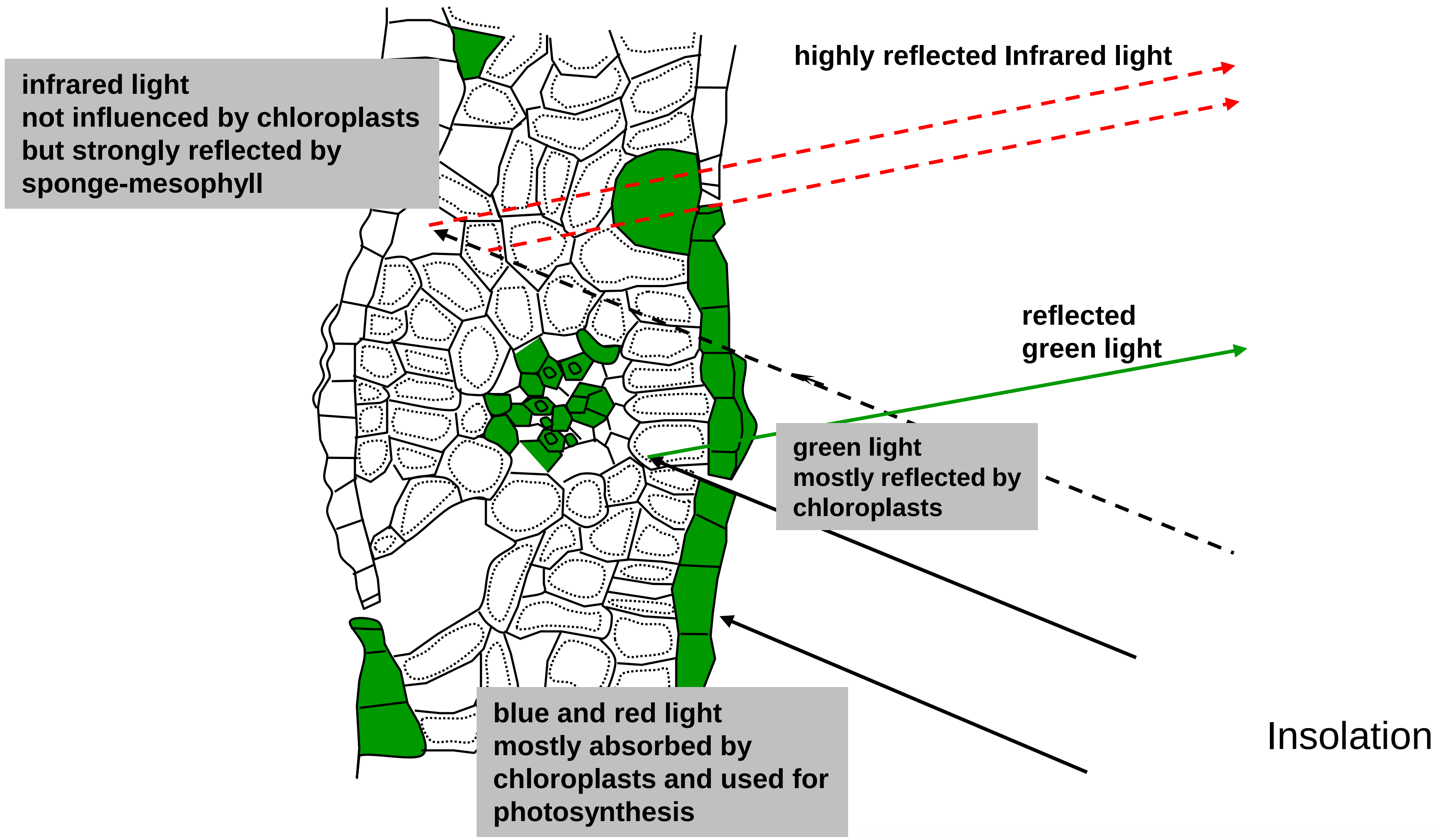
- Vegetation
  - Components of a Single Leaf
  - Absorption features
  - LAI
  - Canopy parameters
  - BRDF

Vegetation

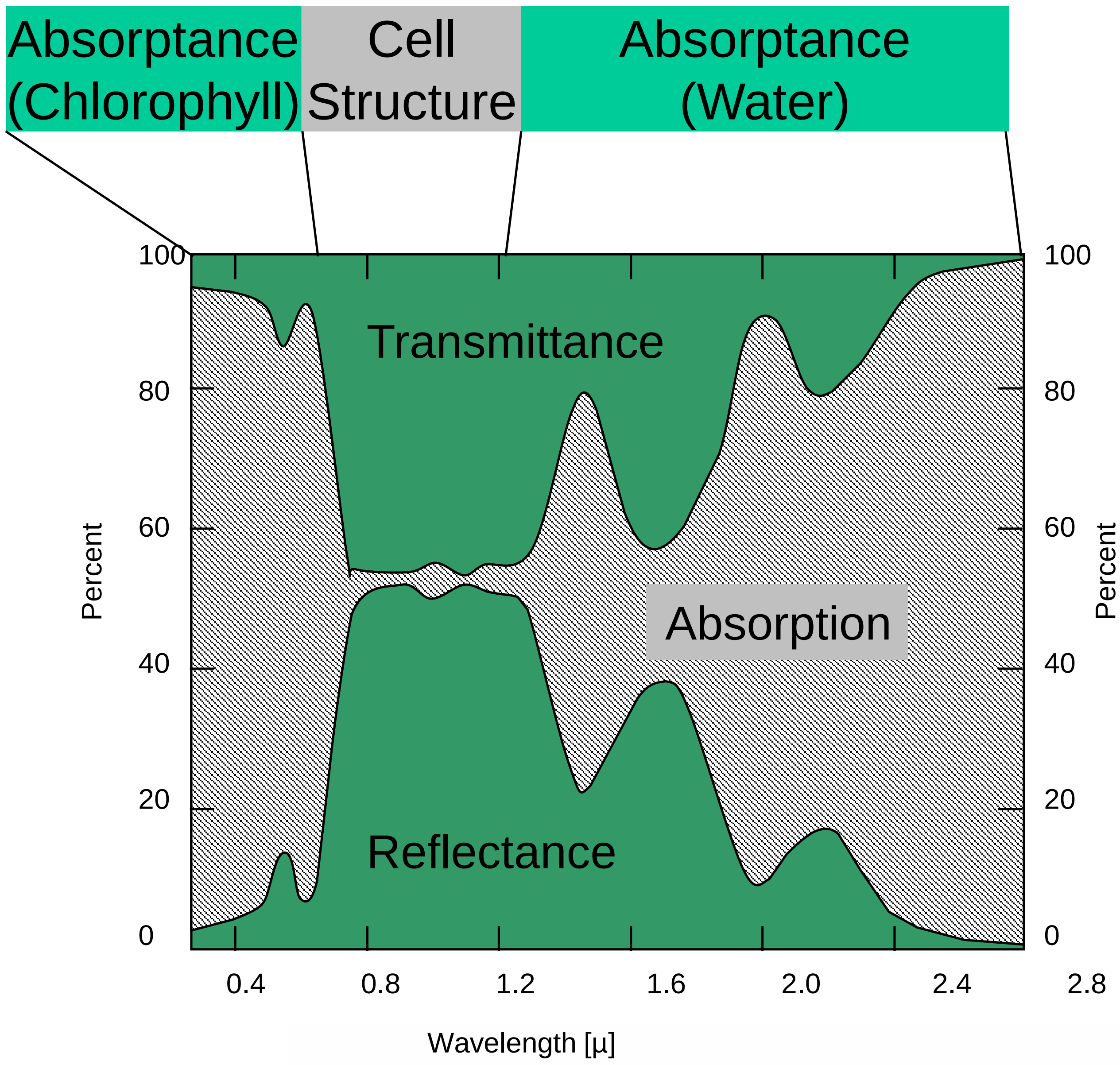
- First part: a single leaf

Vegetation

Leaf cell structure



Colwell 1963



Absorptance (Chlorophyll)
Cell Structure
Absorptance (Water)
Transmittance
Absorption
Reflectance
Percent
Percent
100
80
60
40
20
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
Wavelength [µ]

Vegetation

- 3 groups of effects of light on plants:
  - **Thermal effects** (~70% of absorbed radiation is converted into heat)
  - **Photomorphogenic effects** (i.e. regulation of plant growth in form, size, cell structure, epidermis thickness etc., ~2% of absorbed radiation)
  - **Photosynthetic effects**: photosynthetically active radiation (PAR, ~28% of absorbed radiation),
    $6\ CO_2 + 6\ H_2O \text{ ---}^{PAR}\text{--> } C_6H_{12}O_6 + 6\ O_2$
    - depends on species, leaf thickness, leaf structure, chlorophyll & carotenois content, dry matter content, leaf surface (waxes, leaf hairs…)

Absorption features of plants – some examples:

- 0.28 µm intense Lignin feature, thus extending through the VIS
- Chlorophyll a: 0.420 / 0.490 / 0.660 µm
- Chlorophyll b: 0.435 / 0.643 µm
- α-Carotene: 0.420, 0.440 0.470 µm
- β-Carotene: 0.425 0.450 0.480 µm
- Xanthophyll 0.425, 0.450, 0.475 µm

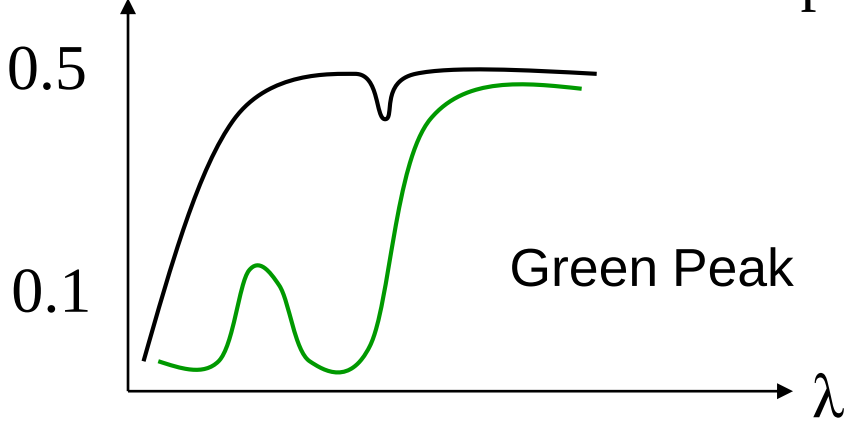
Chlorophyll: electron transition

> 0.9 mainly caused by C-H, O-H, N-H stretches & overtones

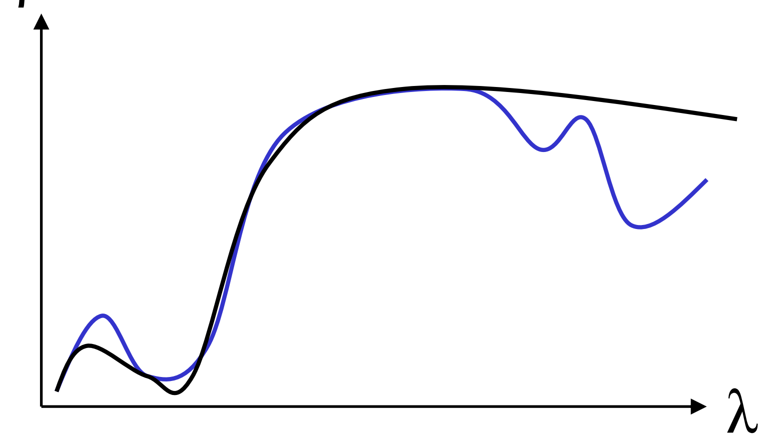
- 0.91 µm protein
- 0.93 µm oil
- 0.97 µm WATER, starch
- 0.99 µm starch
- 1.02 µm protein, n
- 1.04 µm oil
- 1.73 µm wax
- 1.98 µm protein, NITROGEN
- 2.00 µm starch
- 2.06 µm NITROGEN, protein
- 2.08 µm sugar, starch
- 2.10 µm STARCH, cellulose, holocellulose
- 2.13 µm protein, n, tannin
- 2.18 µm protein, NITROGEN
- 2.24 µm protein, n
- 2.25 µm starch
- 2.26 µm lignin
- 2.27 µm cellulose, sugar, starch, lignin
- 2.28 µm starch, cellulose, holocellulose
- 2.30 µm protein, n
- 2.31 µm OIL
- 2.34 µm cellulose, holocellulose
- 2.35 µm cellulose, protein, n
- 2.38 µm LIGNIN

Vegetation

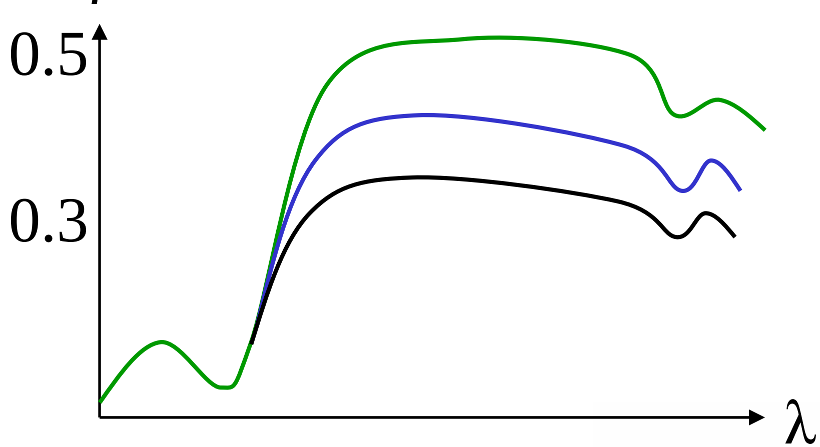
With & without chlorophyll



With & without water



Cell structure



Cell spacings filled with

Air (drying plant)

Water (healthy plant)

Oil

Vegetation

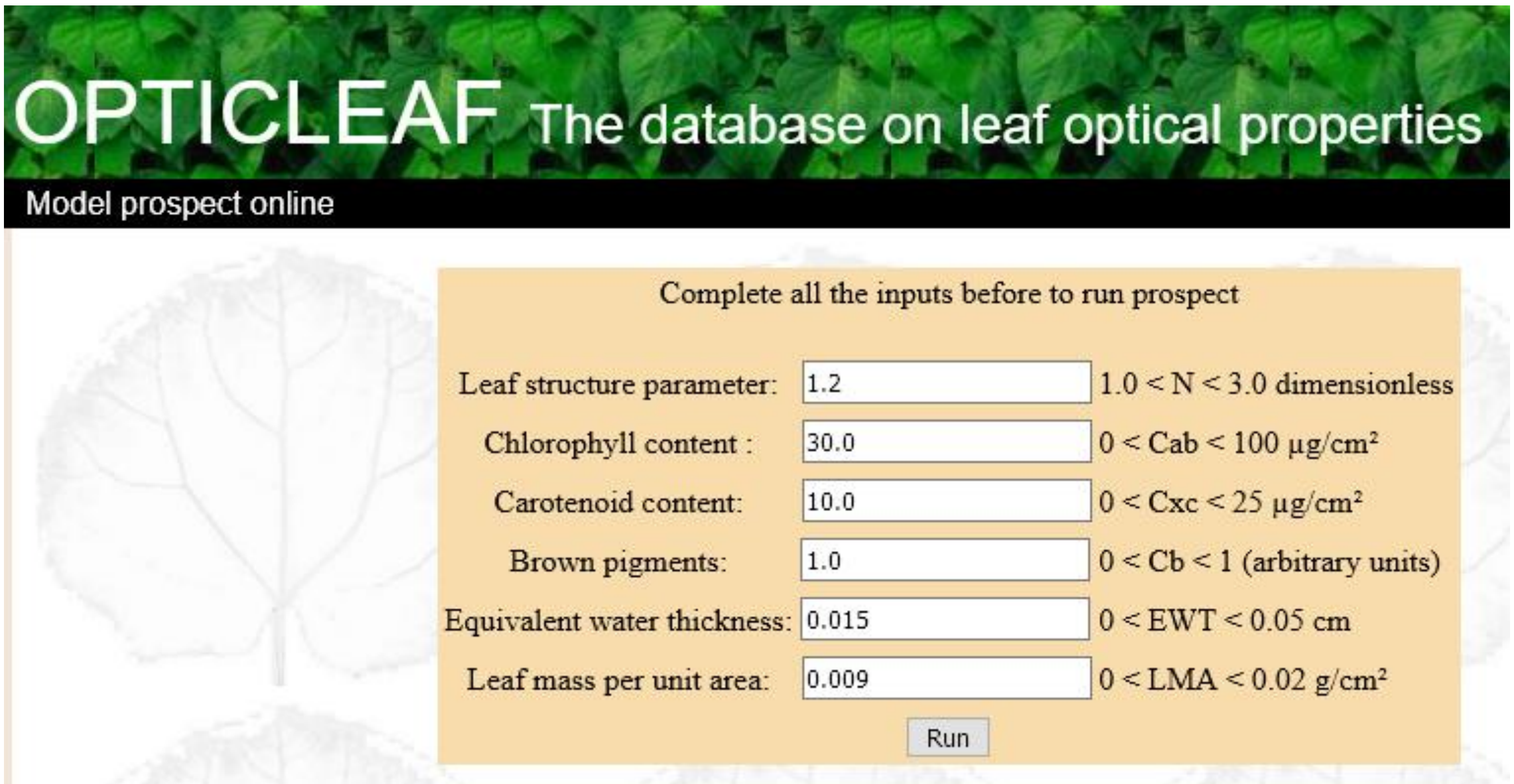
- Examples for radiative transfer models:
  - PROSPECT: leaf radiation transfer model
  - SAIL: Canopy reflectance model

➔ Model inversion in order to derive biochemical composition of plants

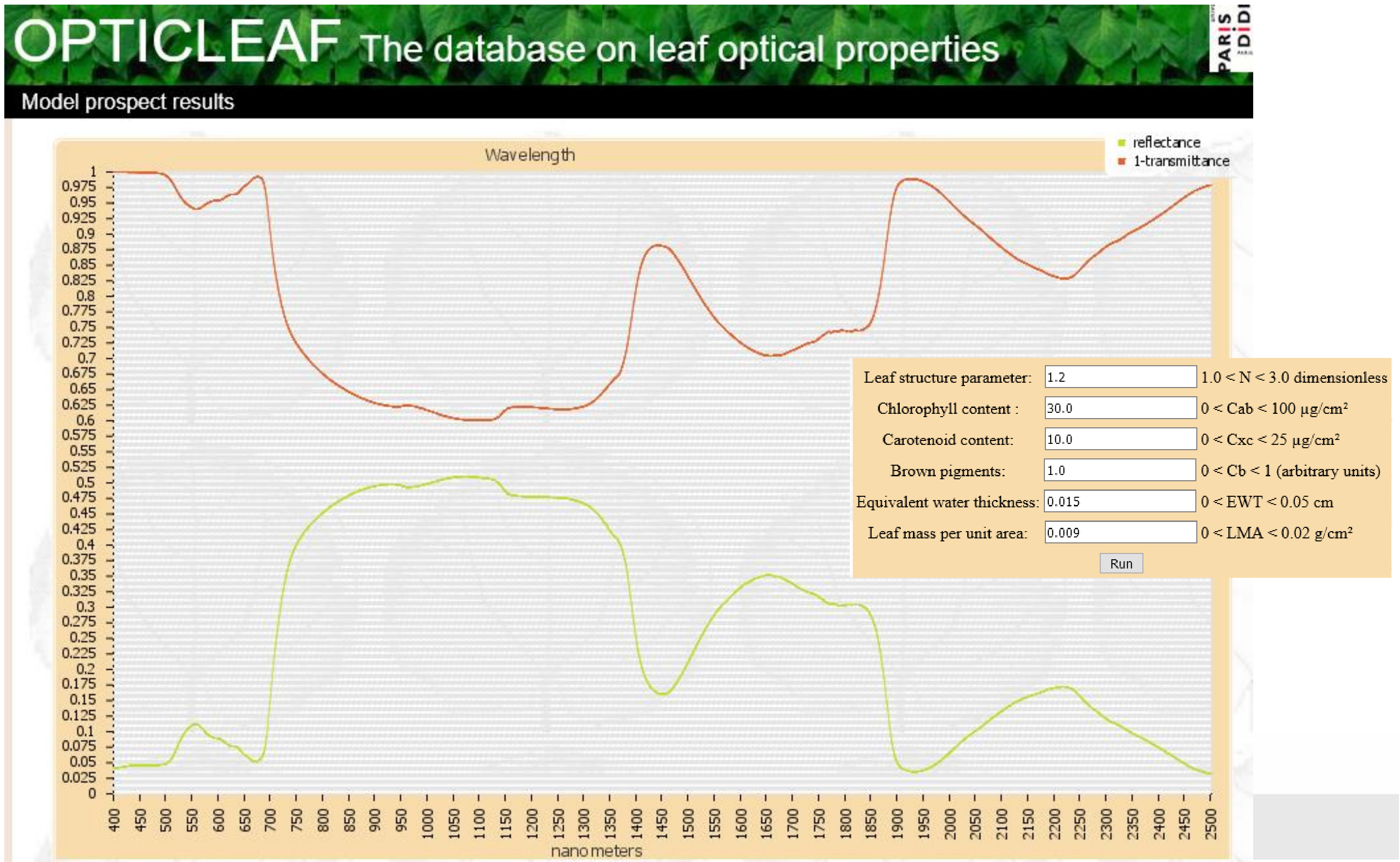
Vegetation

- Online at:

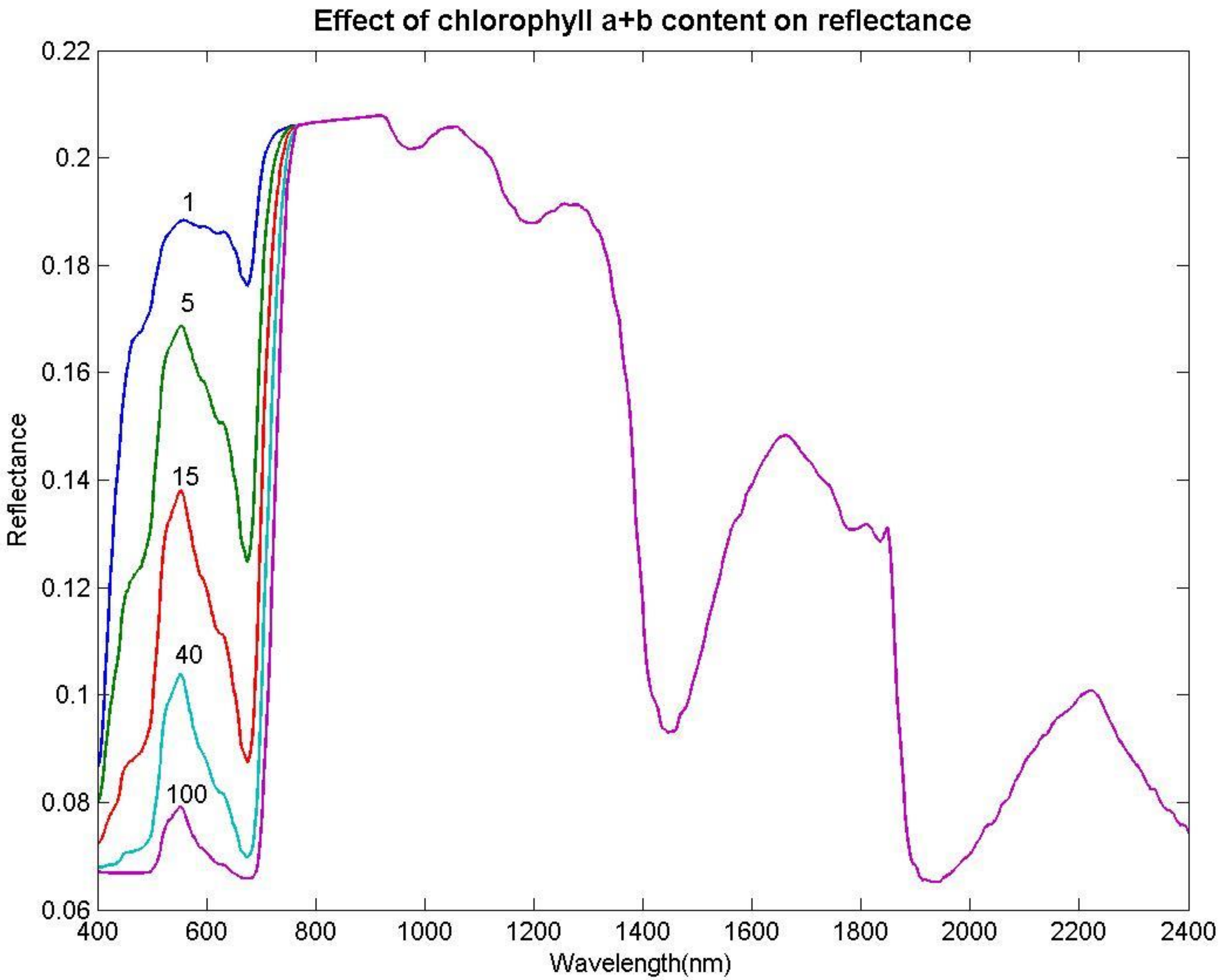
  http://opticleaf.ipgp.fr/index.php?page=prospect



Vegetation

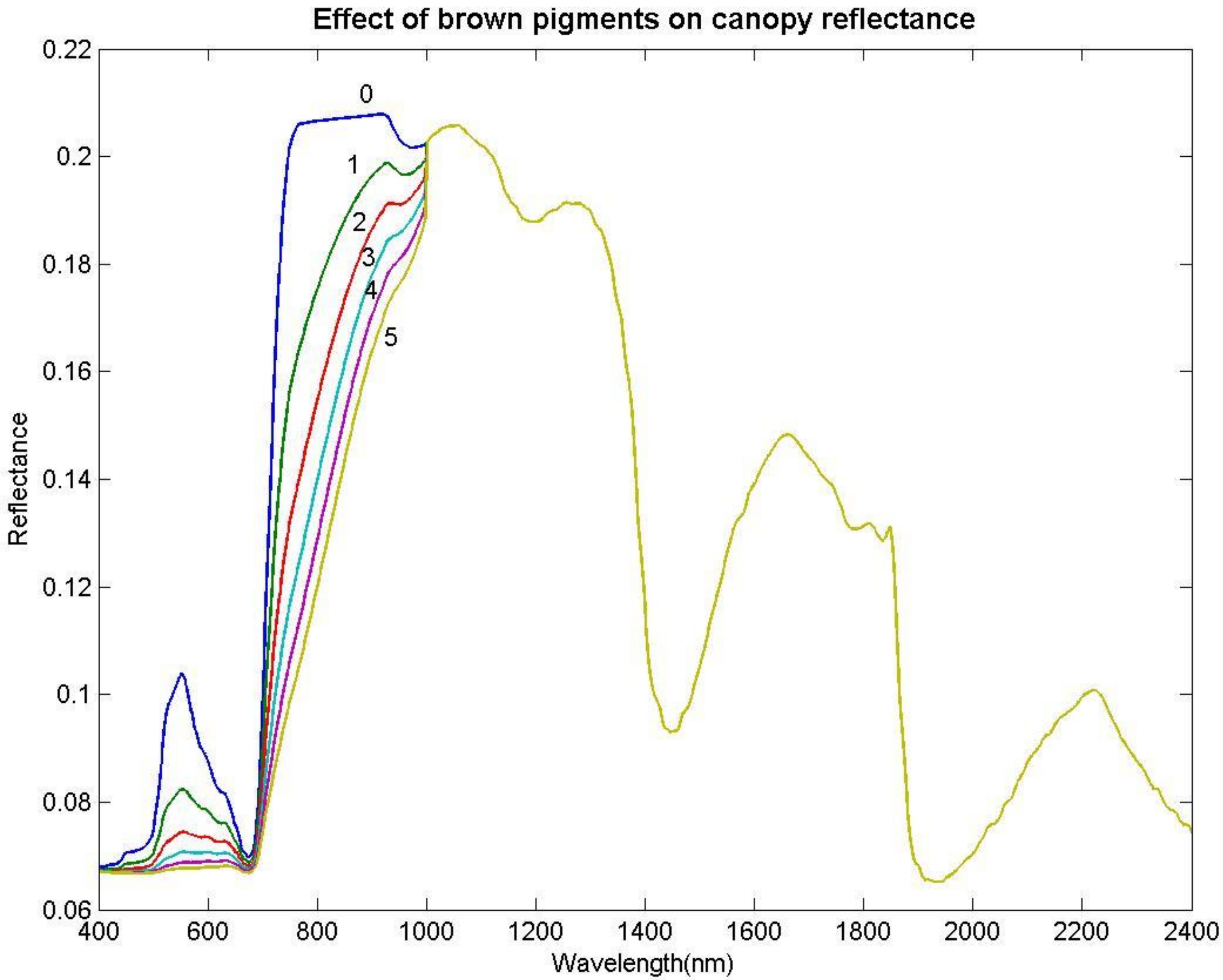

OPTICLEAF The database on leaf optical properties
Model prospect results
Wavelength
reflectance
1-transmittance
nanometers
Leaf structure parameter: 1.2 1.0 < N < 3.0 dimensionless
Chlorophyll content : 30.0 0 < Cab < 100 µg/cm²
Carotenoid content: 10.0 0 < Cxc < 25 µg/cm²
Brown pigments: 1.0 0 < Cb < 1 (arbitrary units)
Equivalent water thickness: 0.015 0 < EWT < 0.05 cm
Leaf mass per unit area: 0.009 0 < LMA < 0.02 g/cm²
Run

Vegetation



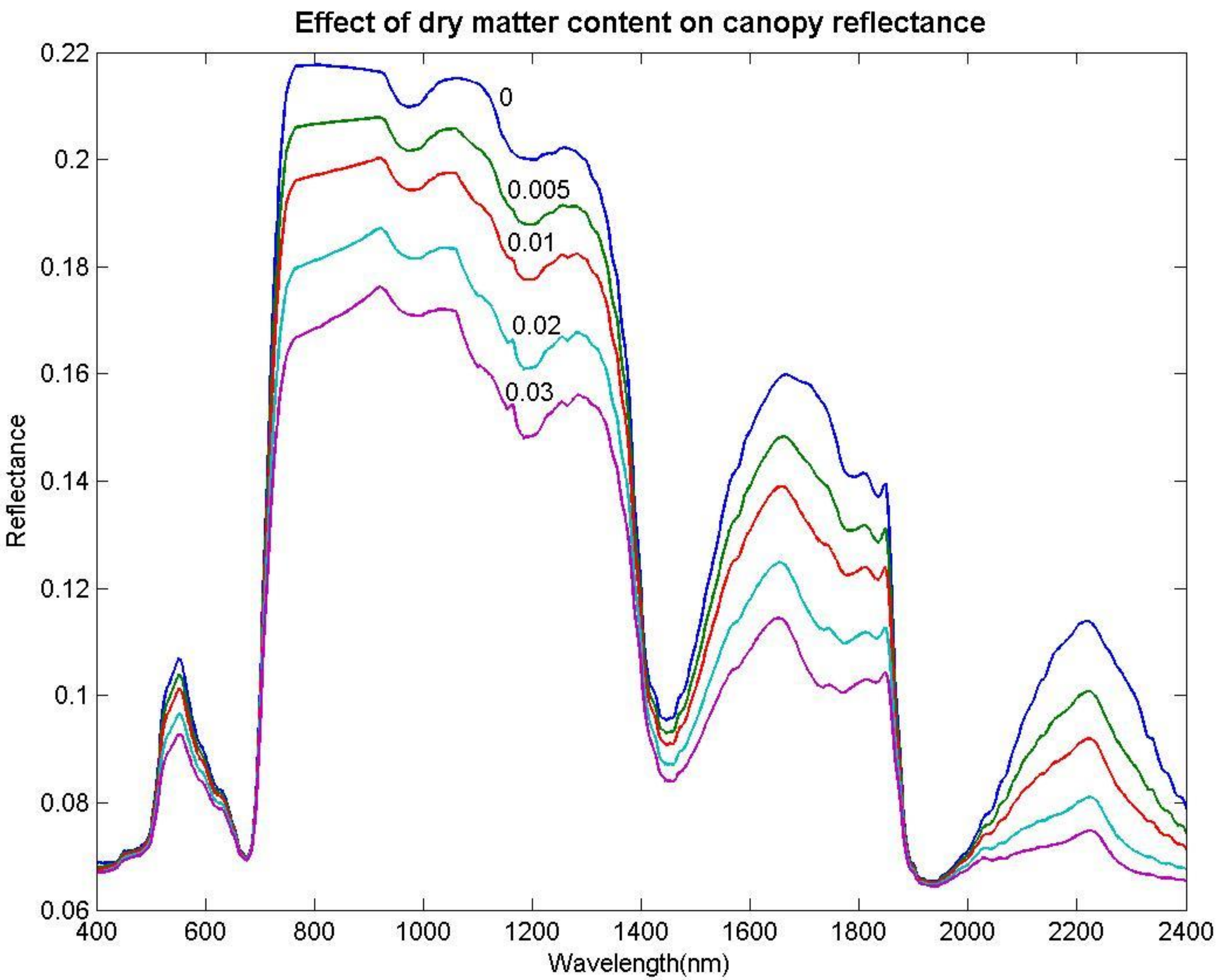
Effect of chlorophyll a+b content on reflectance
Reflectance
Wavelength(nm)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
1
5
15
40
100

Vegetation



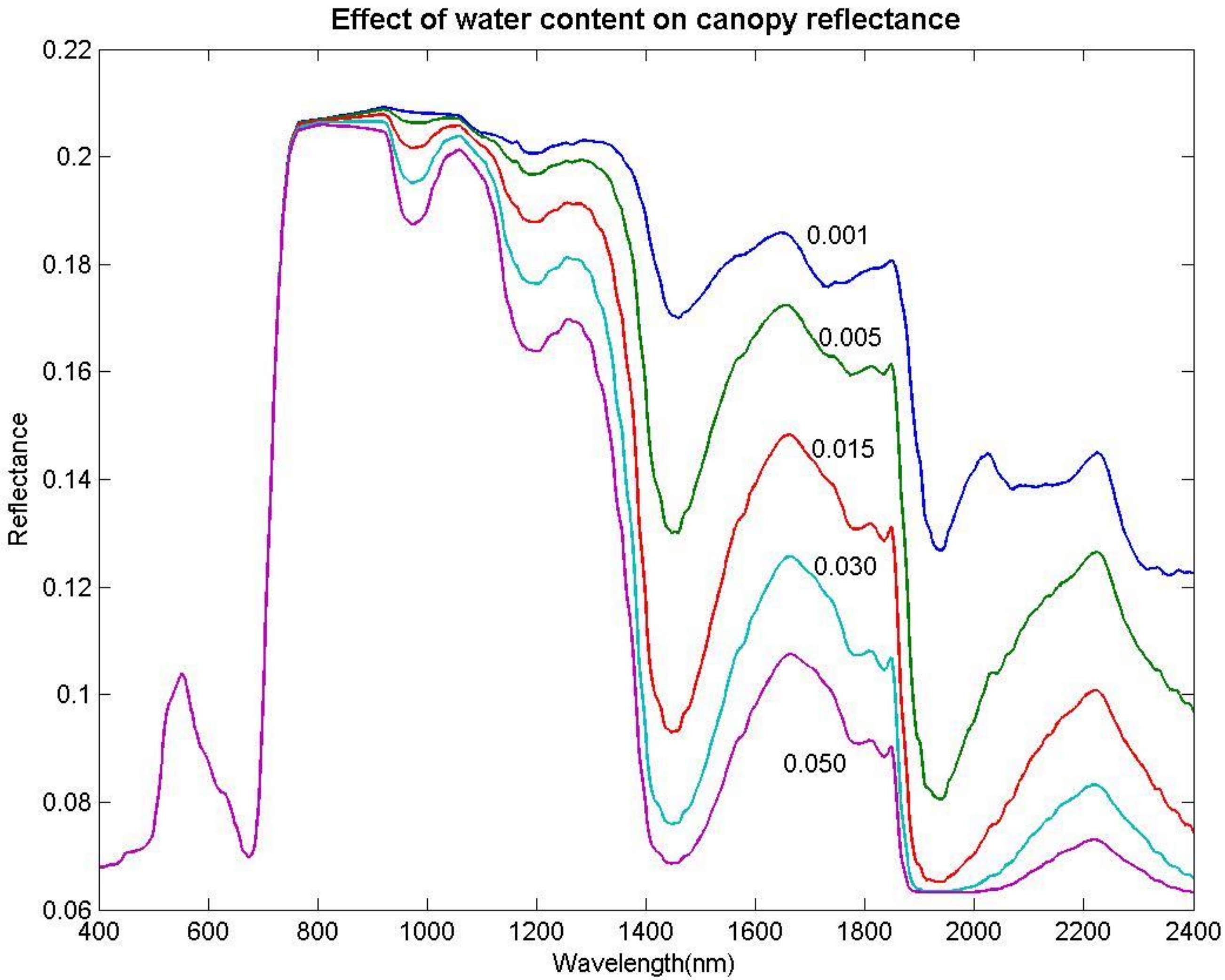
Effect of brown pigments on canopy reflectance
Reflectance
Wavelength(nm)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
0
1
2
3
4
5

Vegetation



Deutsches Zentrum
für Luft- und Raumfahrt e.V.
in der Helmholtz-Gemeinschaft

Vegetation



Effect of water content on canopy reflectance
Reflectance
Wavelength(nm)
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
0.001
0.005
0.015
0.030
0.050

Vegetation

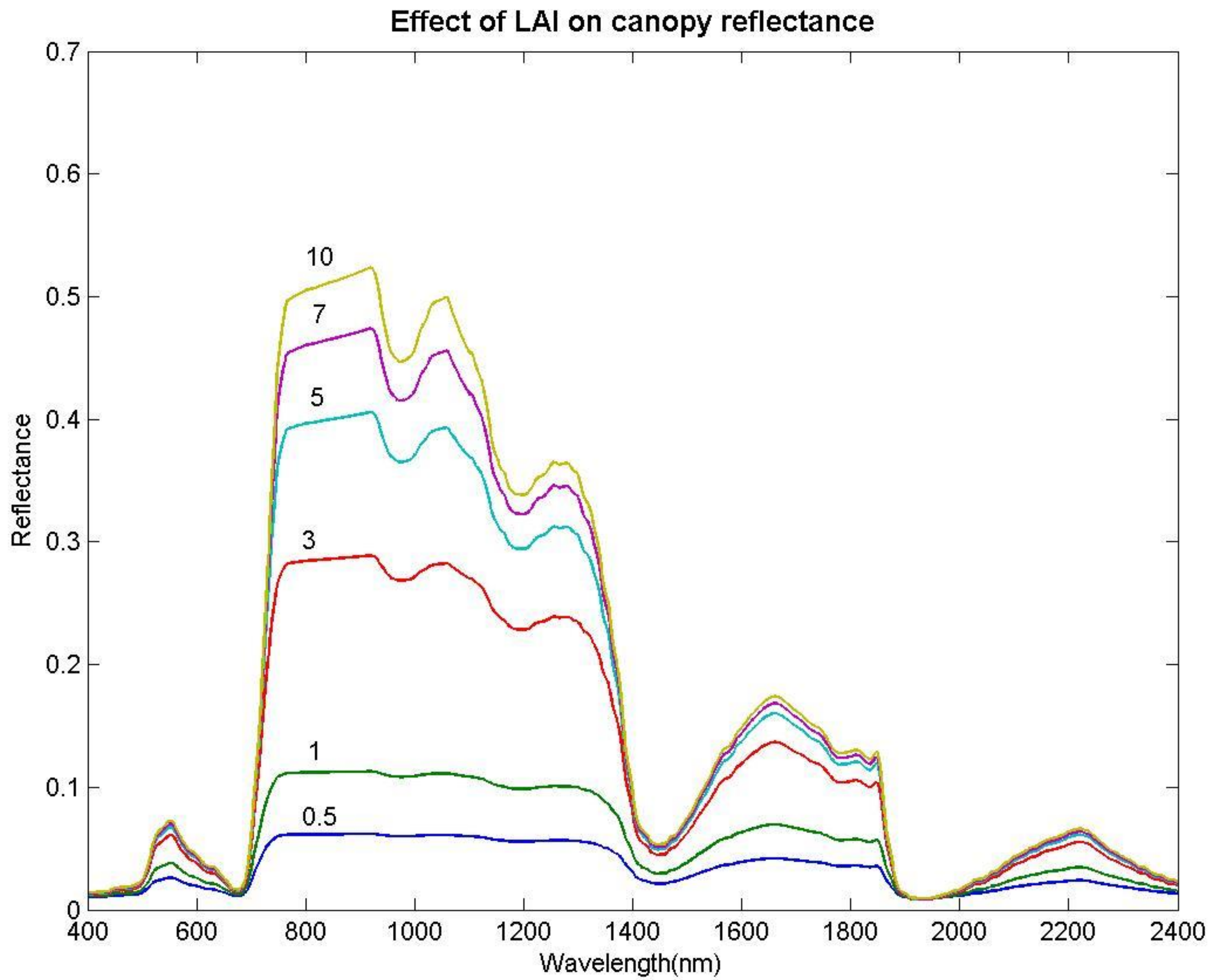
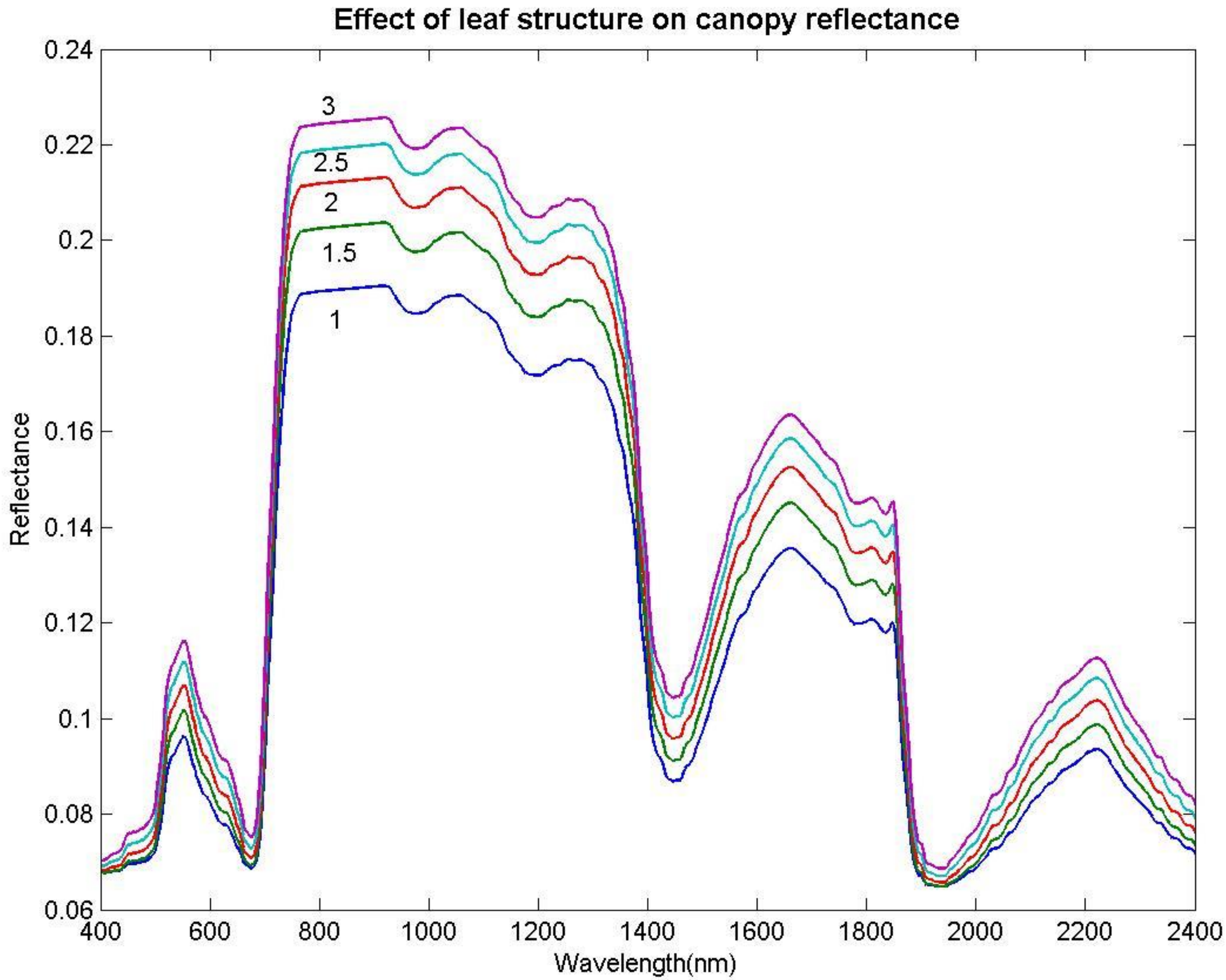


Fig. based on SAIL/PROSPECT simulations.

In literature: saturation at LAI ~ 6

!

Vegetation



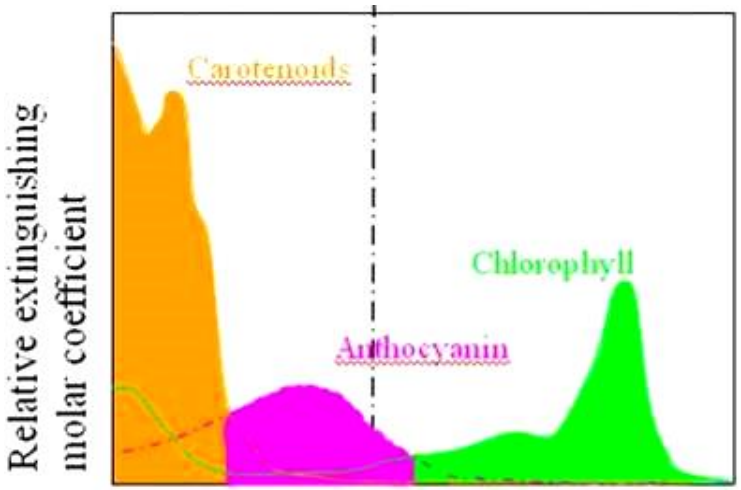
Leaf Structure Parameter depends on species

i.e. leaf type, mono- or dicotyle etc.

Vegetation

- Senescense:
  - Chlorophyll less stable than carotenes & xanthophylls ➔ yellow color
  - Fructose, glucose, starch, protein are either withdrawn by the plant or consumed by microbiotic activity
  - Most stable: tannins ➔ brown color
  - Plant water decreases, no masking of features above ~1.1μm
    ➔ biochemical features are now visible
  - Holocellulose and Lignin(10-35% of dry weigth): stable, main components of plant litter
  - Also: cellulose (main component, but mostly mixed with lignin, cellulose or xylan), waxes, terpenes, polysaccharide

Leaf Colors and associated dominating Pigments



400 nm 700 nm

During spring/summer, spectral reflectance characteristics (colors) of carotenoids and anthocyanin are masked by those from chlorophyll. During fall, chlorophyll is decomposed and stored in trunks and branches. This demasks the spectral characteristics of carotenoids and anthocyanin.

Chlorophyll

Anthocyanin

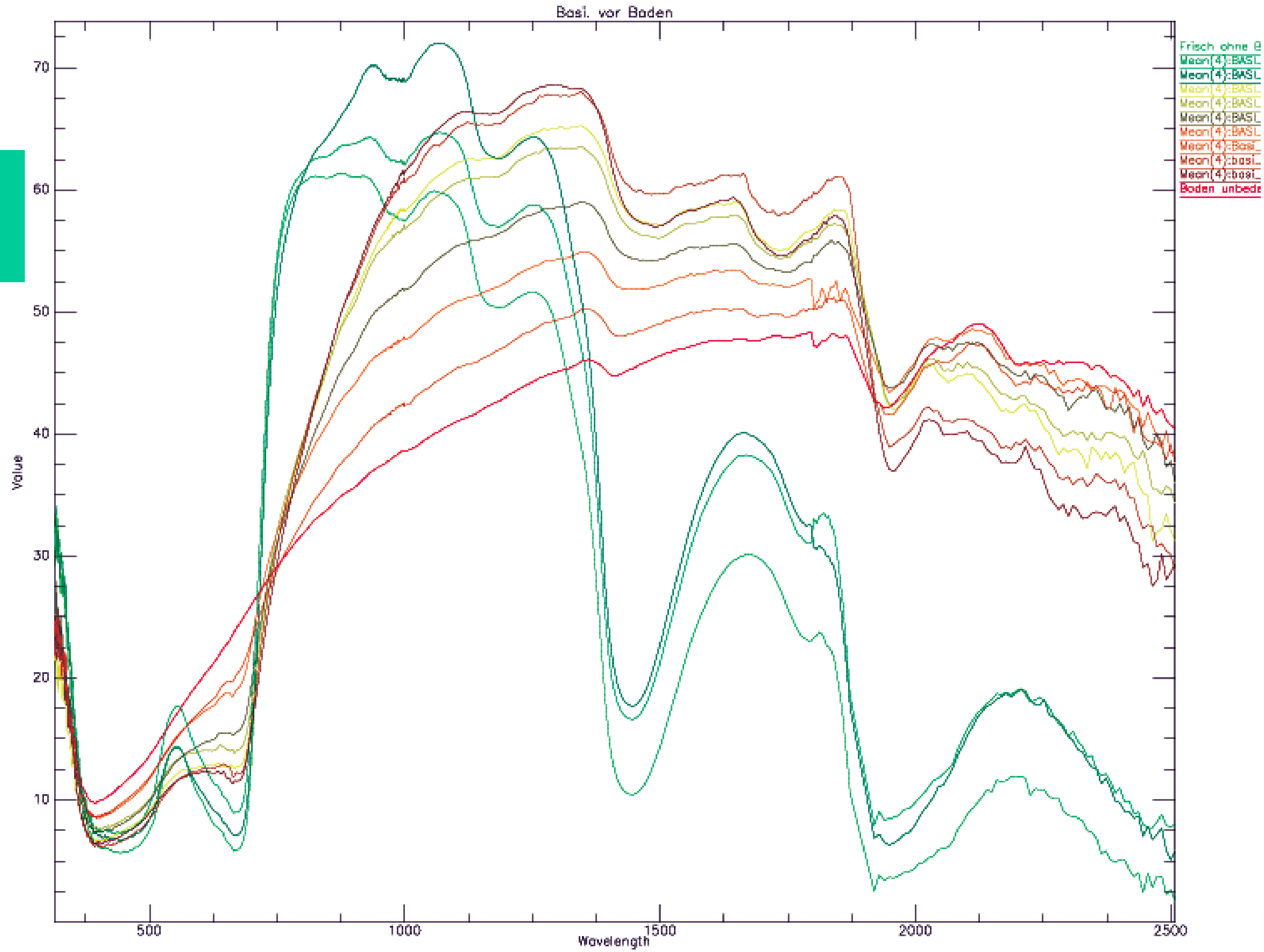
Carotene

Xanthophyll

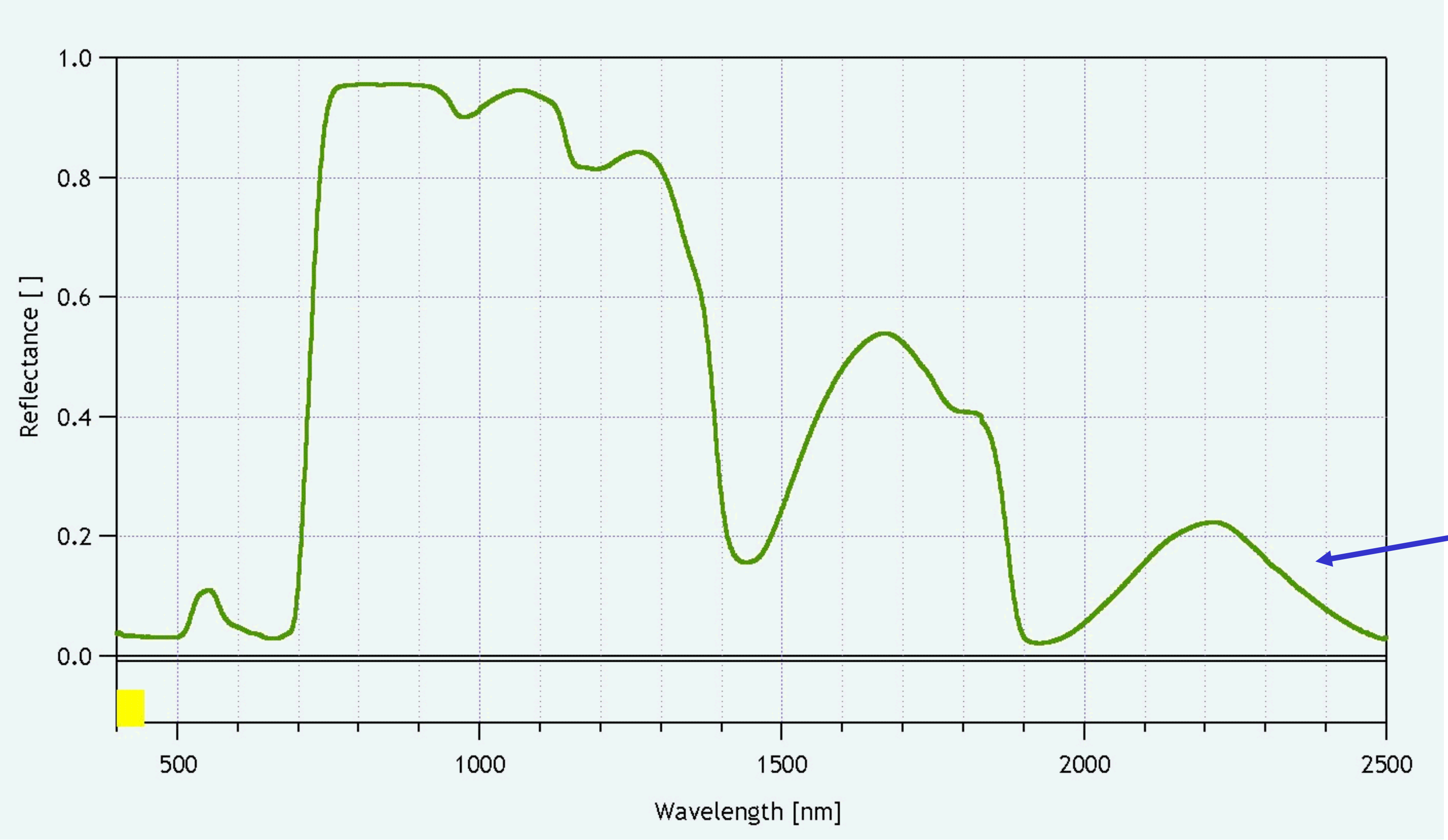
Carotenoids

Vegetation

Senescence of leaves
+ soil background



Decay of a Leaf (*Ficus benjamina)*



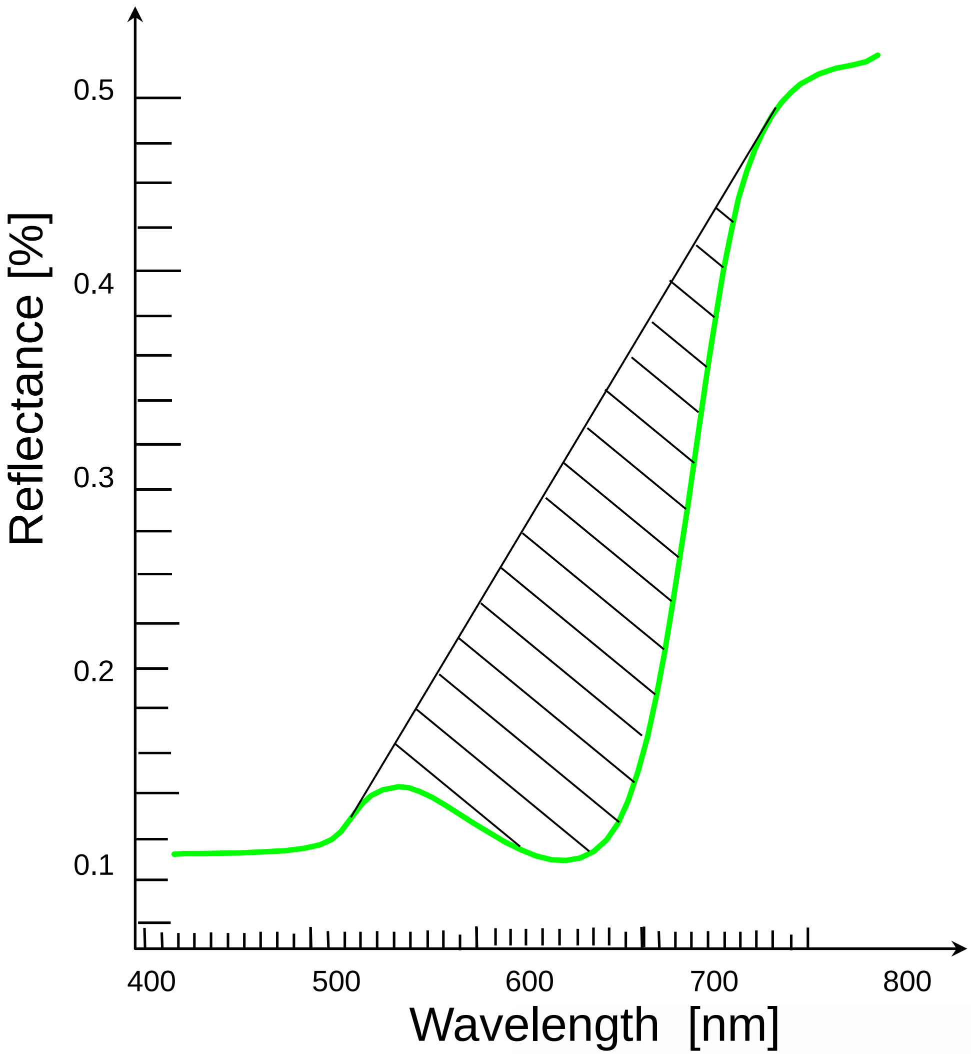
undisturbed leaf

Each time step is 10 min.; total duration 8 hrs

Measurement is reflectance plus reflected transmittance

Source:
Bartholomeus, H., and Schaepman M. (2004)

Chlorophyll Absorption Integral



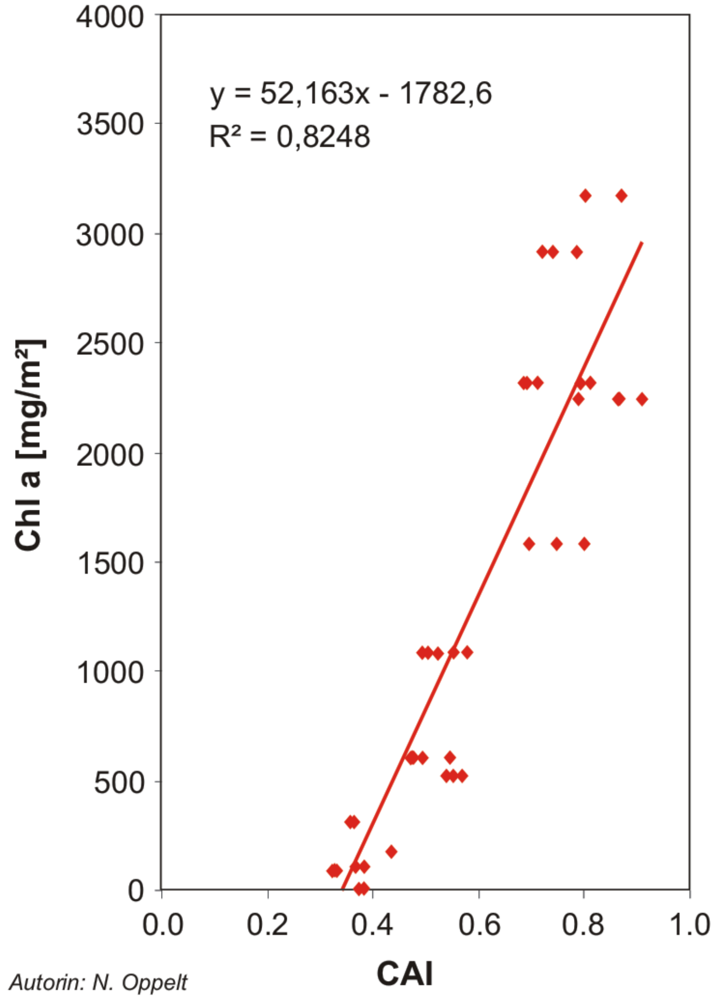
Chlorophyll Absorptions Integral (CAI)

correlated with

- Chlorophyll content (Biomass)
- Nitrogen (vital state)

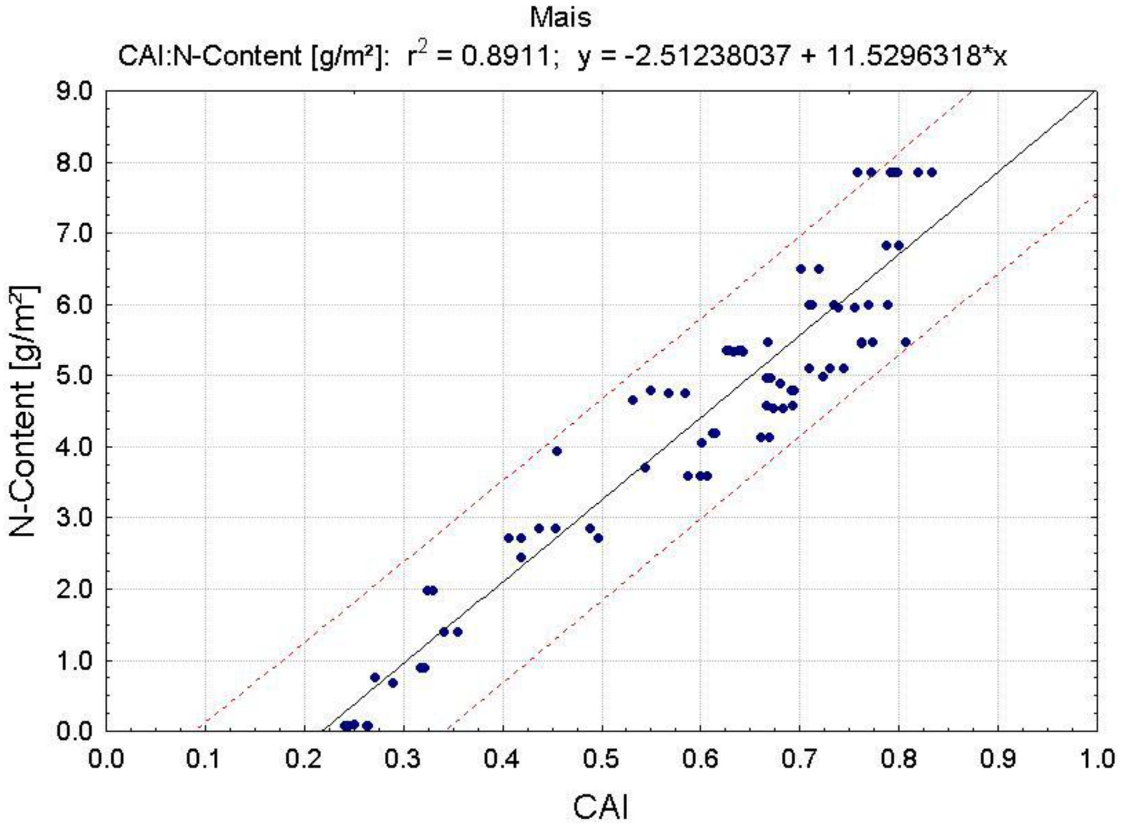
The larger the area the higher the content of chlorophyll and nitrogen

Correlation of CAI/Chlorophyll and CAI/Nitrogen



Autorin: N. Oppelt

The CAI correlates with chlorophyll- and Nitrogen contents of Vegetation canopies (Oppelt, 2002).



Biannual test series on corn (1999-2000)

Vegetation

- Needles instead of leaves

Vegetation

- Second part: whole plants & canopies

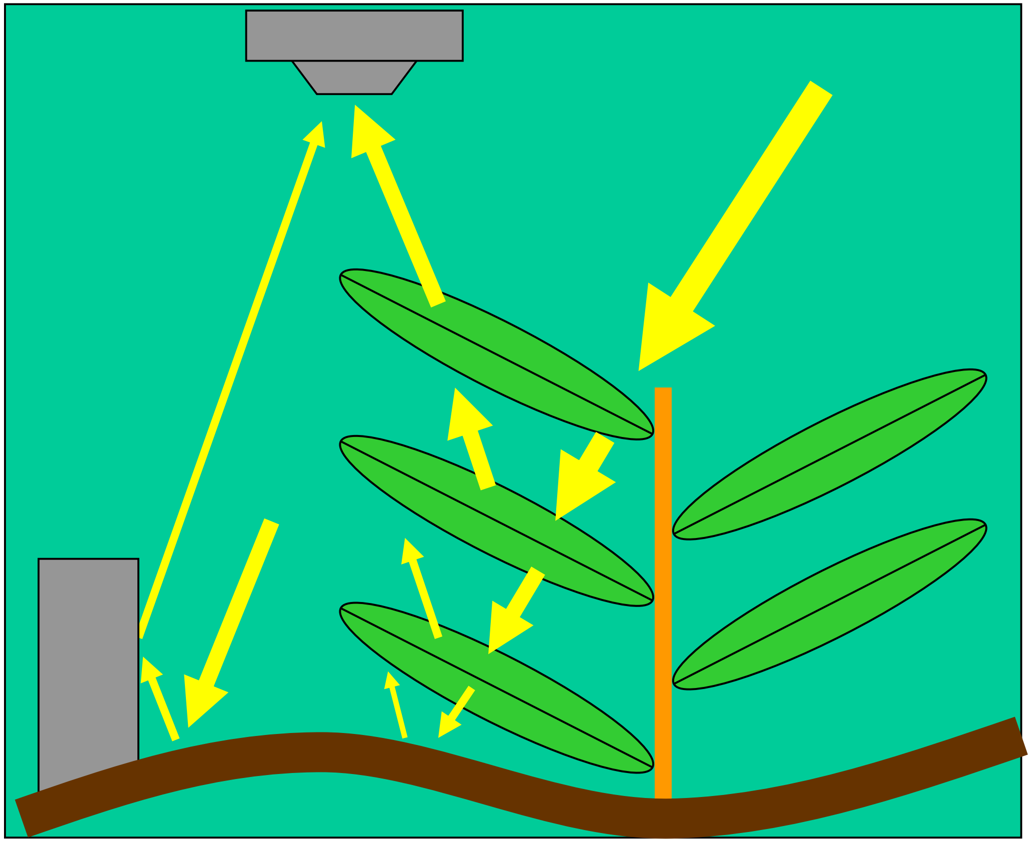
Vegetation

- LAI: gouverns energy & mass exchanges like evapotranspiration, primary production, crop yield etc.

- f_{APAR} (fraction of absorbed photosynthetically active radiation): related to biomass production

Vegetation

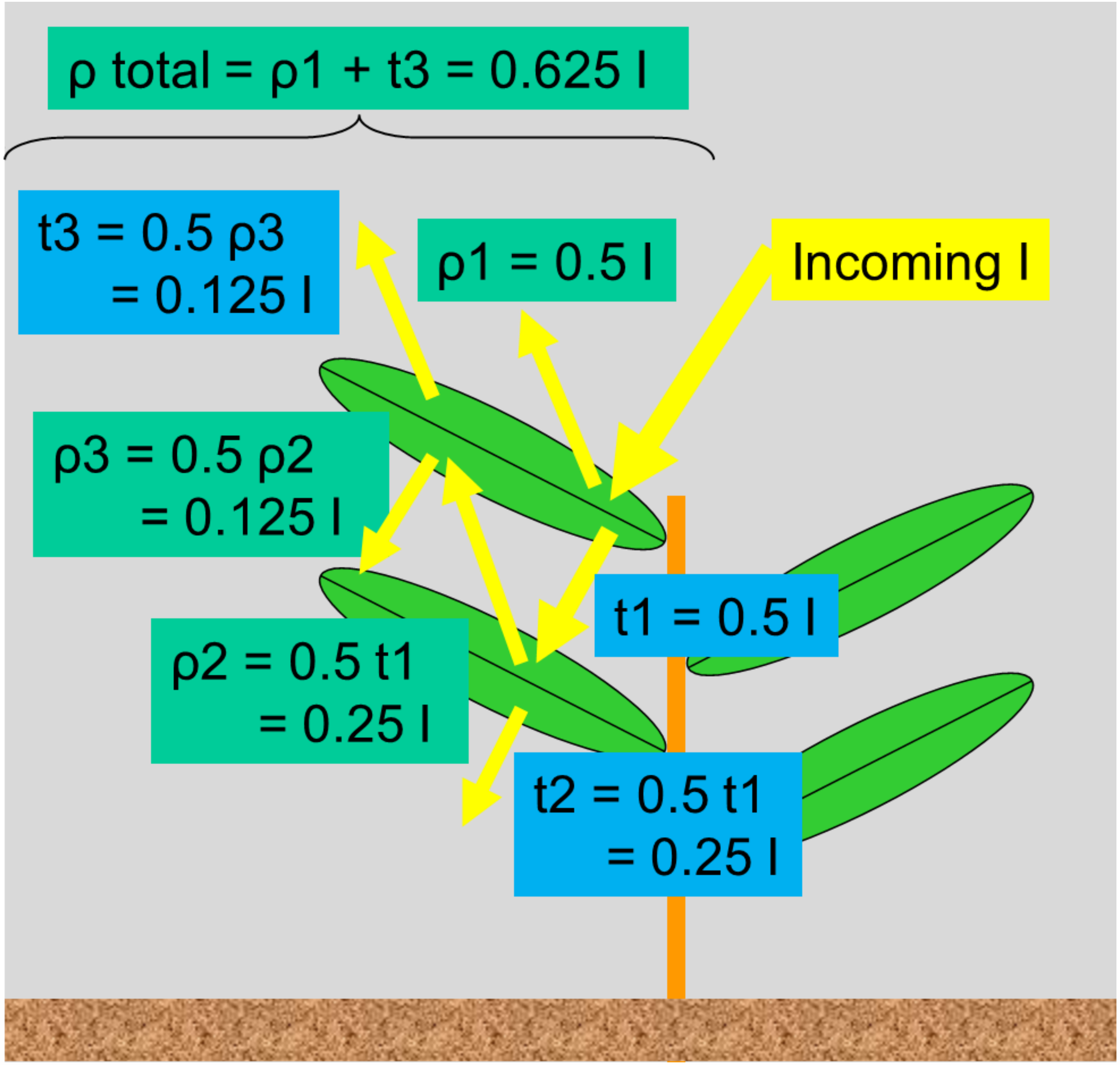
- Non-linear mixtures:
  - If large transmission occurs (plant canopies!)
  - If multiple reflections between one or more objects in one GIFOV



Vegetation

I: Incoming Radiation
t: Transmitted
ρ : Reflected

For simplification:
no absorption,
ρ = 0.5,
t = 0.5



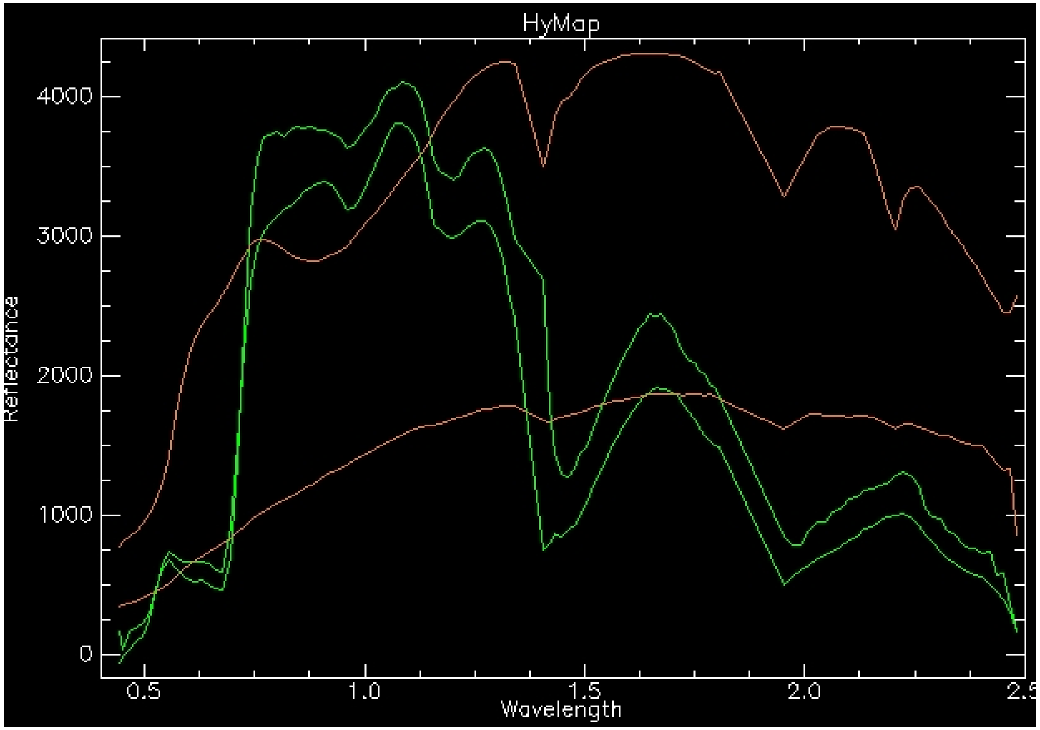
Original concept by Hoffer 1978

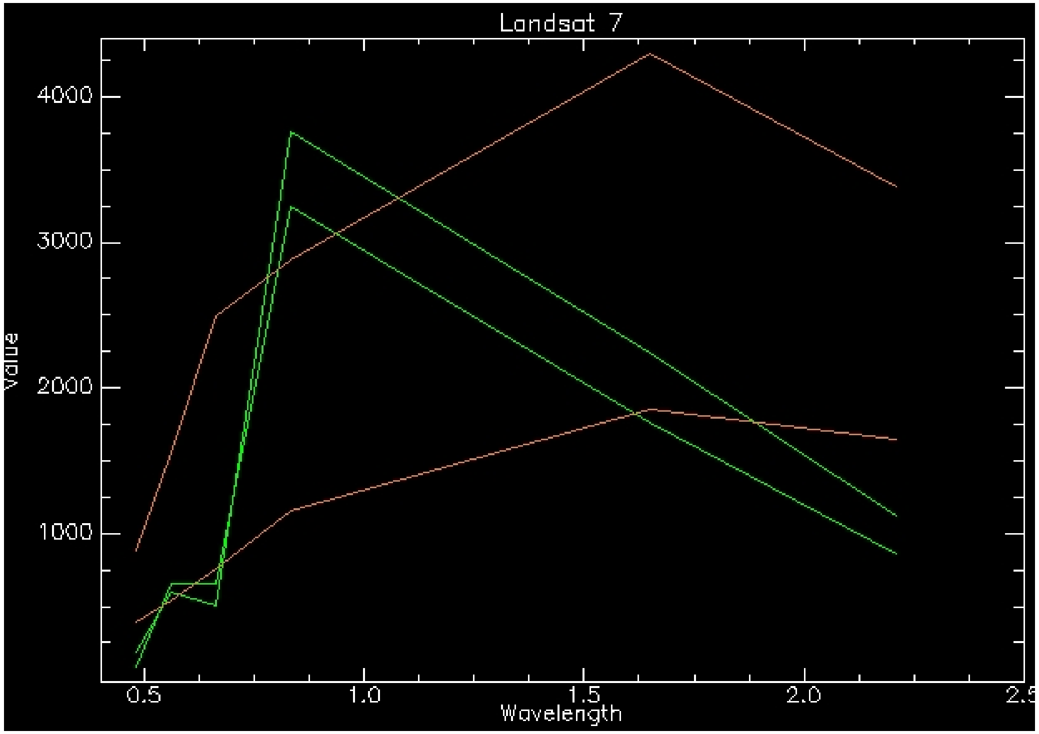
Vegetation

$$\rho_\lambda = f(\rho_{S\lambda}, Cab, Cw, N, LAI, \theta z, \theta v, \phi)$$

with	$\rho_{S\lambda}$	Spectral reflectance of the underlying soil (equation 1)
	Cab	Leaf chlorophyll (a+b) content (µg/cm^2)
	Cw	Leaf water content (cm)
	N	Leaf structure parameter (N=1.5 for monocotyls, N=2.5 for dicotyls)
	LAI	Leaf area (one-sided) per unit soil surface (m^2/m^2)

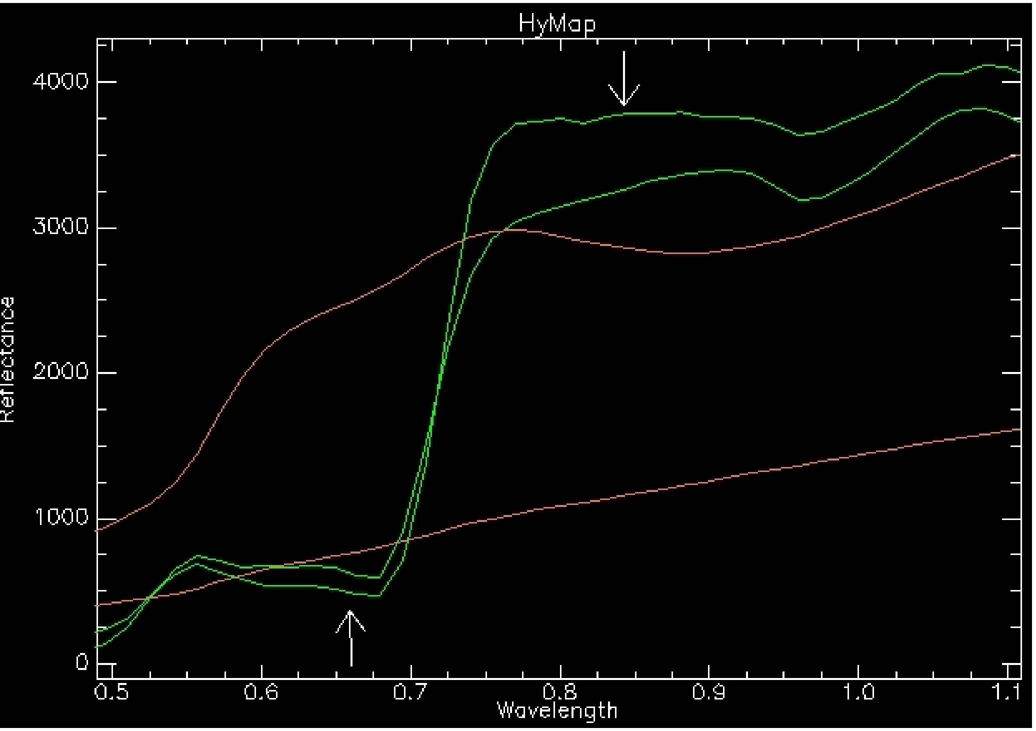
Vegetation - Indices

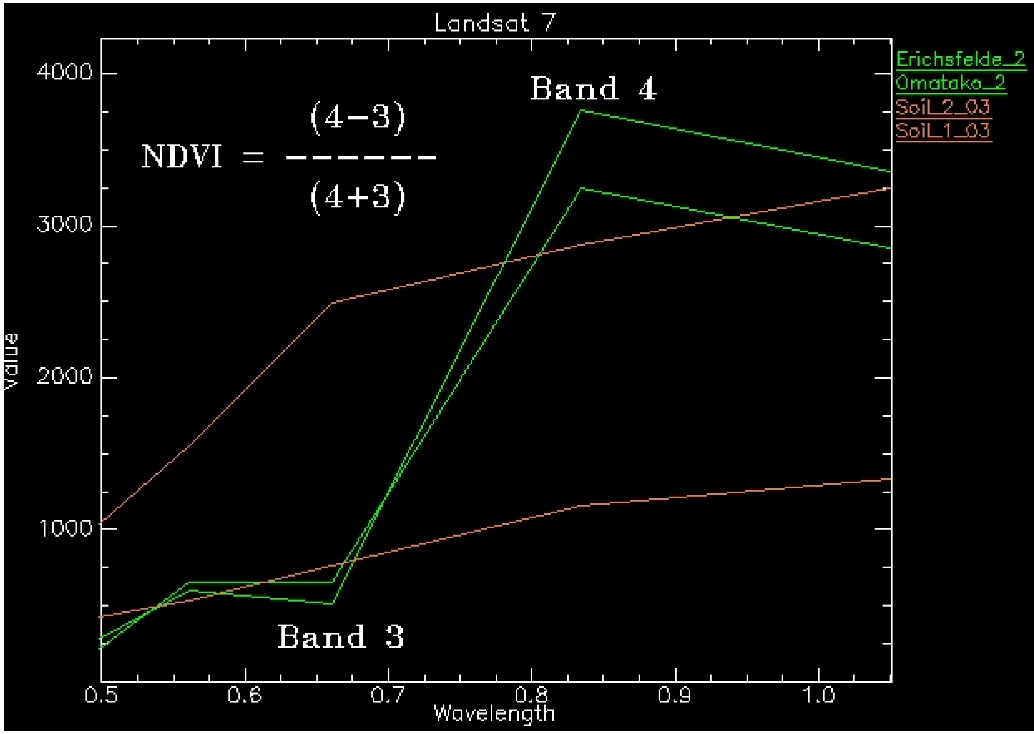




Green: Vegetation
Brown: Soil

Vegetation - Indices



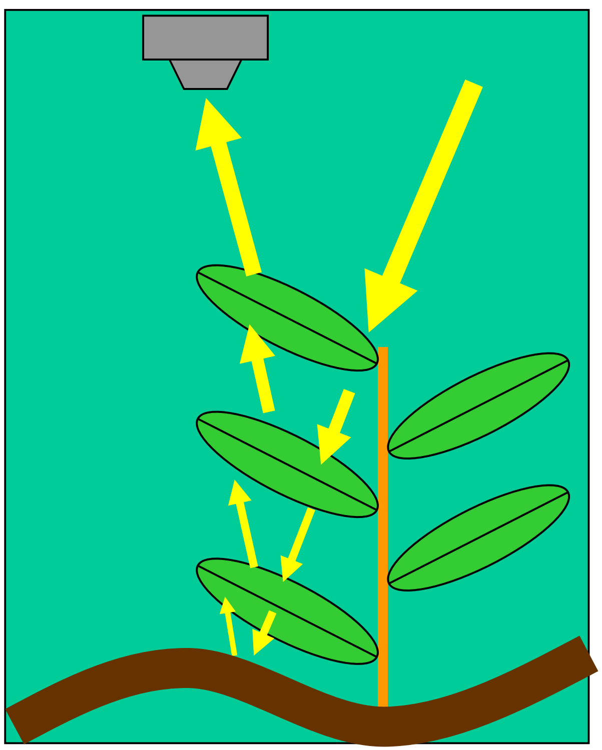


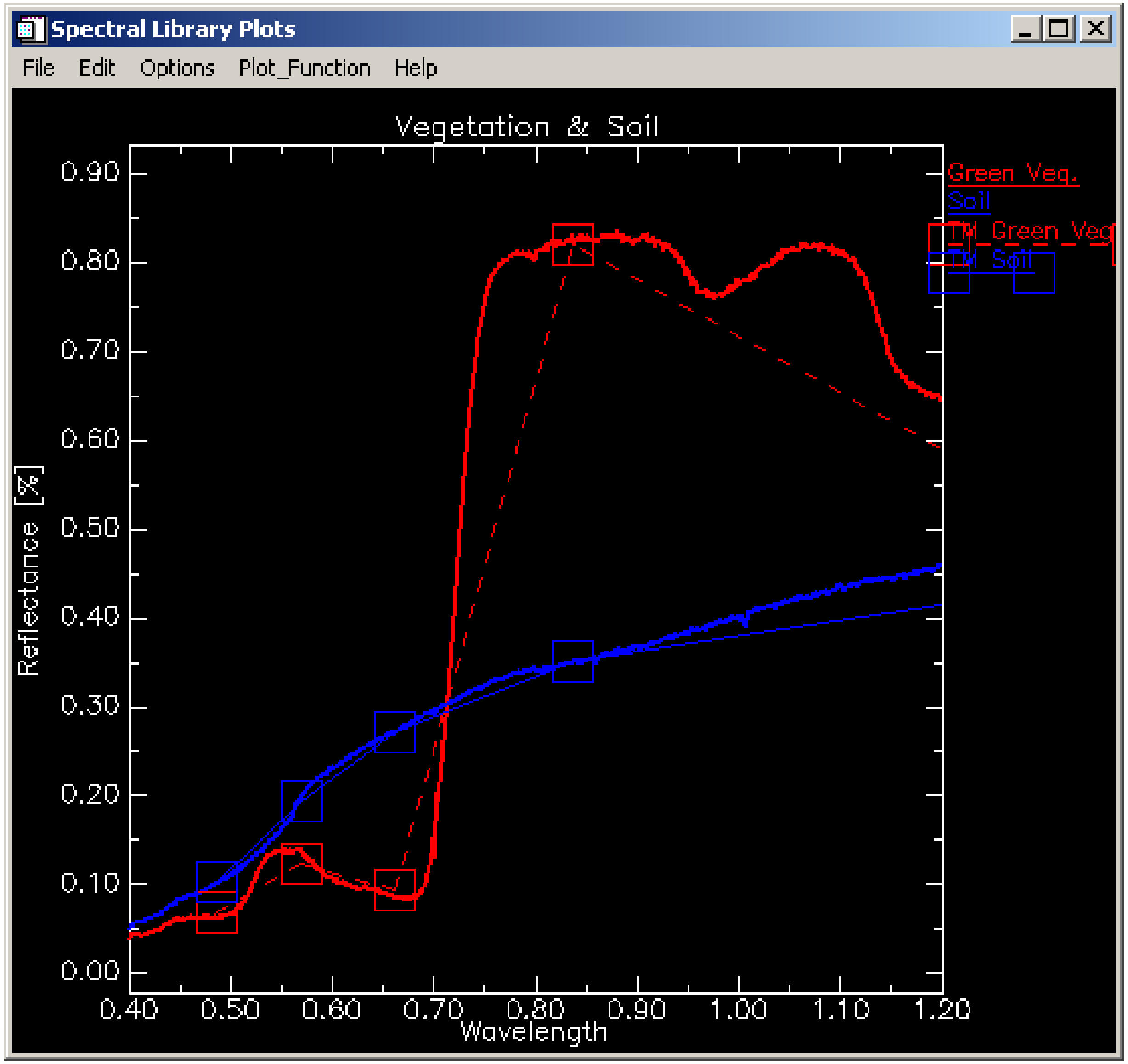
Normalized Difference Vegetation Index (NDVI) = (NIR – Red) / (NIR + Red)
Scaling (theoretic) from -1 till +1
Typical values:

Forest & dense vegetation ~0.8	Grassland ~0.6
Soil ~0.1 – 0.2	Urban areas ~0 – 0.2

Vegetation

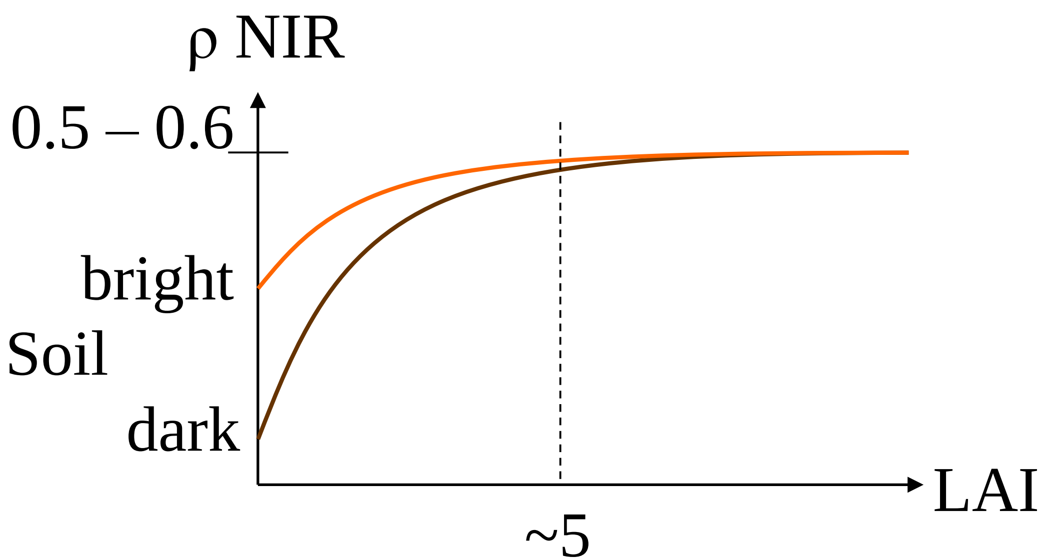
NDVI & LAI

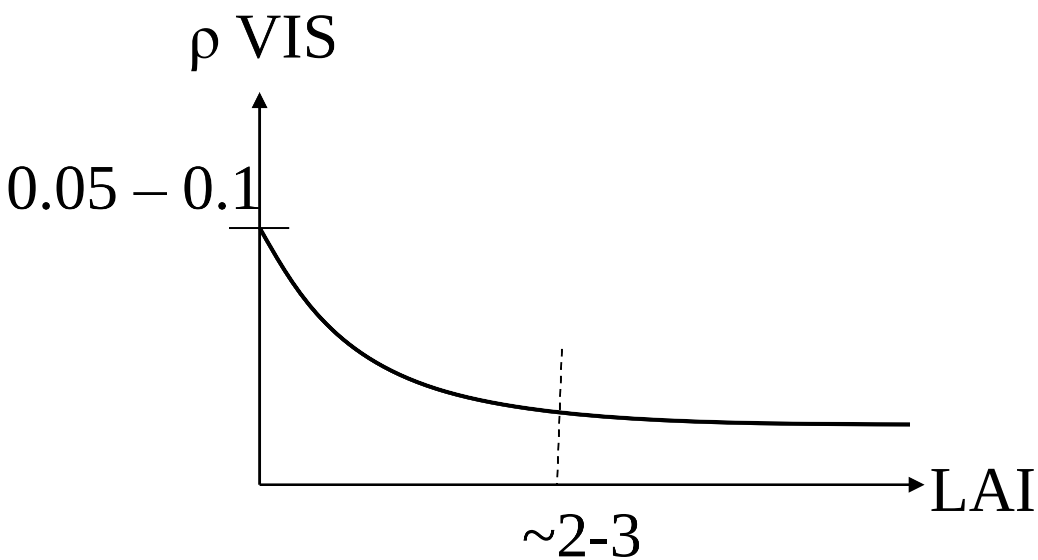




Vegetation

Schematic illustration of LAI saturation



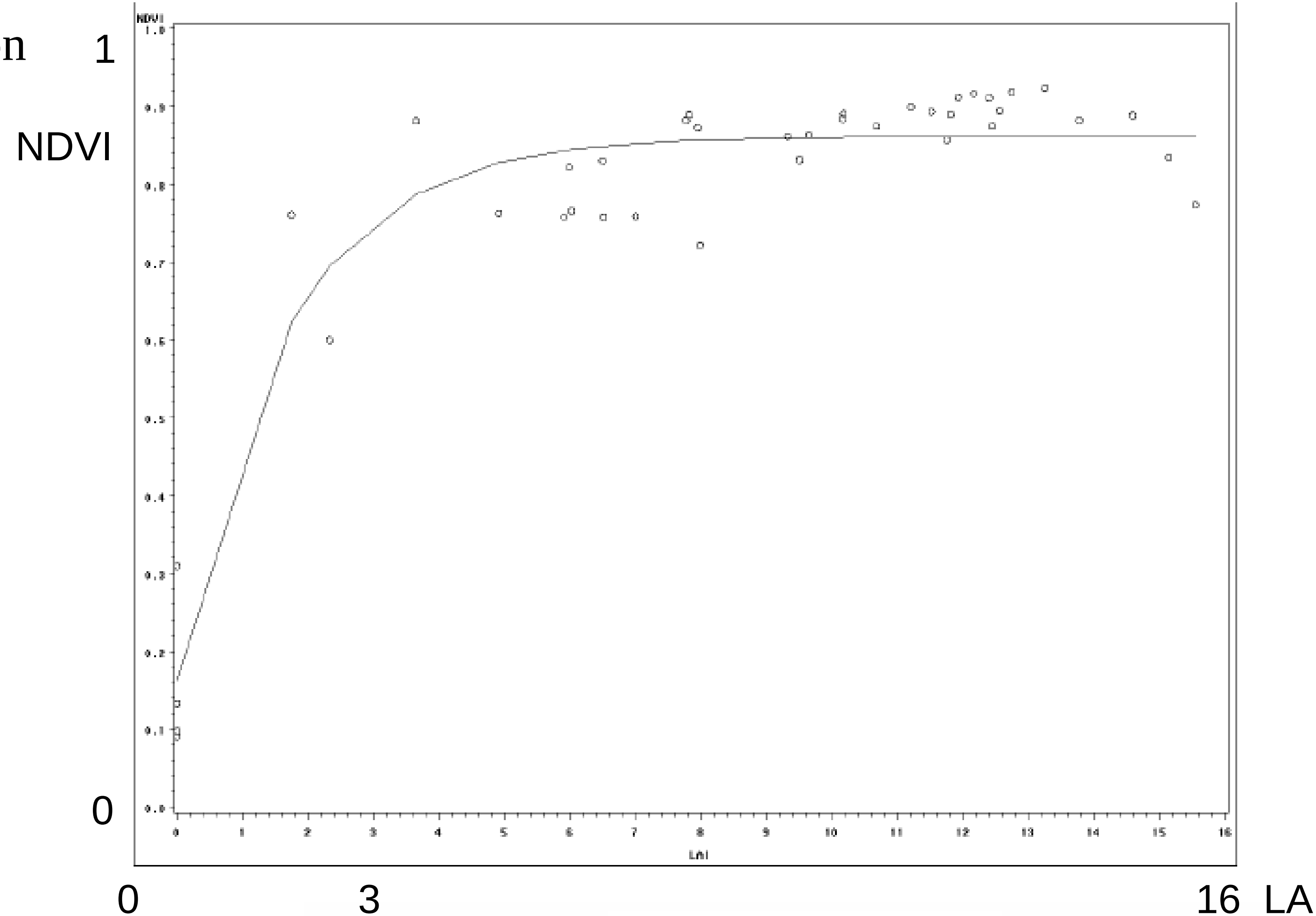


ρ NIR = f (LAI, cell structure, soil brightness)

ρ VIS = f (LAI, chlorophyll content)

Saturation with > LAI, since no radiation reaches lowest foliage layer

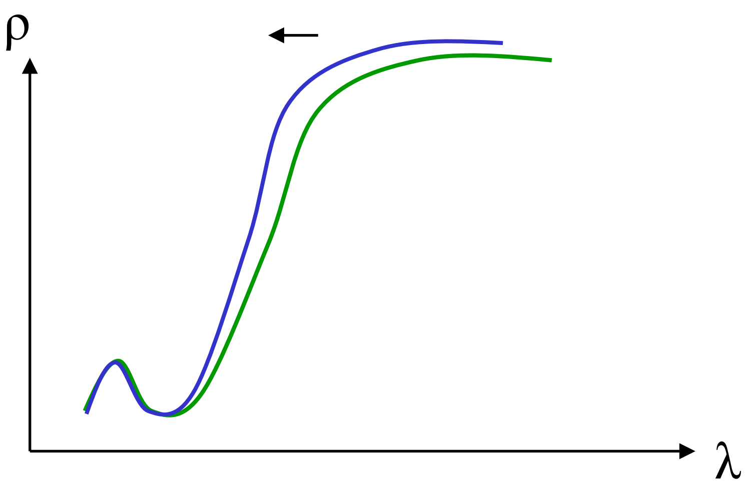
Vegetation



Roberts et al., submitted

Vegetation

- Red Edge:
  > Chlorophyll => shift to longer wavelength
  < Chlorophyll (Stress) => Blueshift
- But: > LAI => also shift to longer wavelength (saturation at LAI ~4)
- „Sharpness“ of Edge



RedEdge – Parameterization:

REP = f (LAI, chlorophyll, leaf inclination angle)
➔ independent from soil reflectance, only minor impact of solar zenith angle

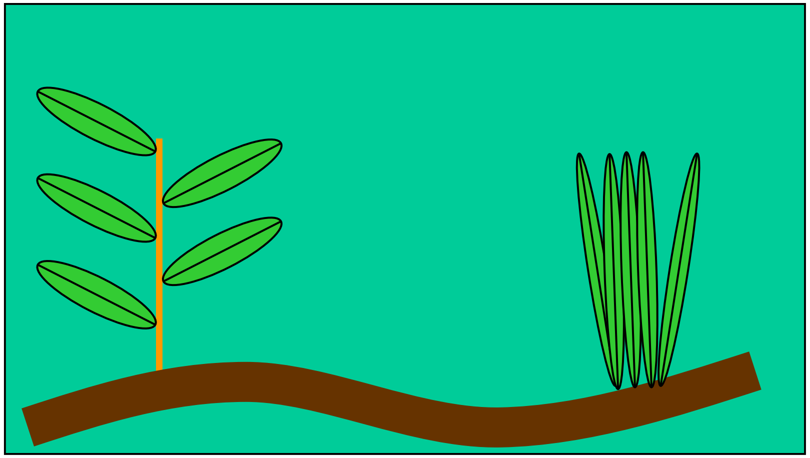
- Inflexion Point (Wendepunkt)
- Ratios:

$R_i = (670 + 780) / 2$

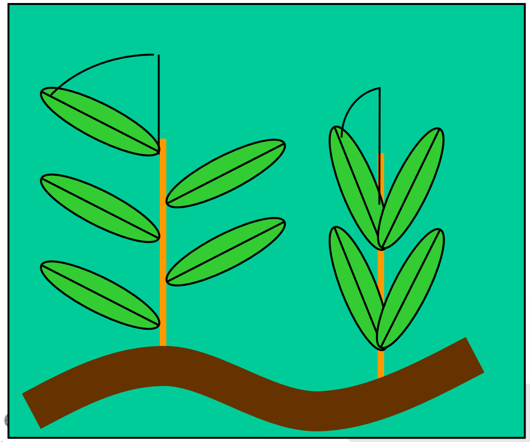
$REP = 700 + 40 * ((Ri - 700) / (740 - 700))$

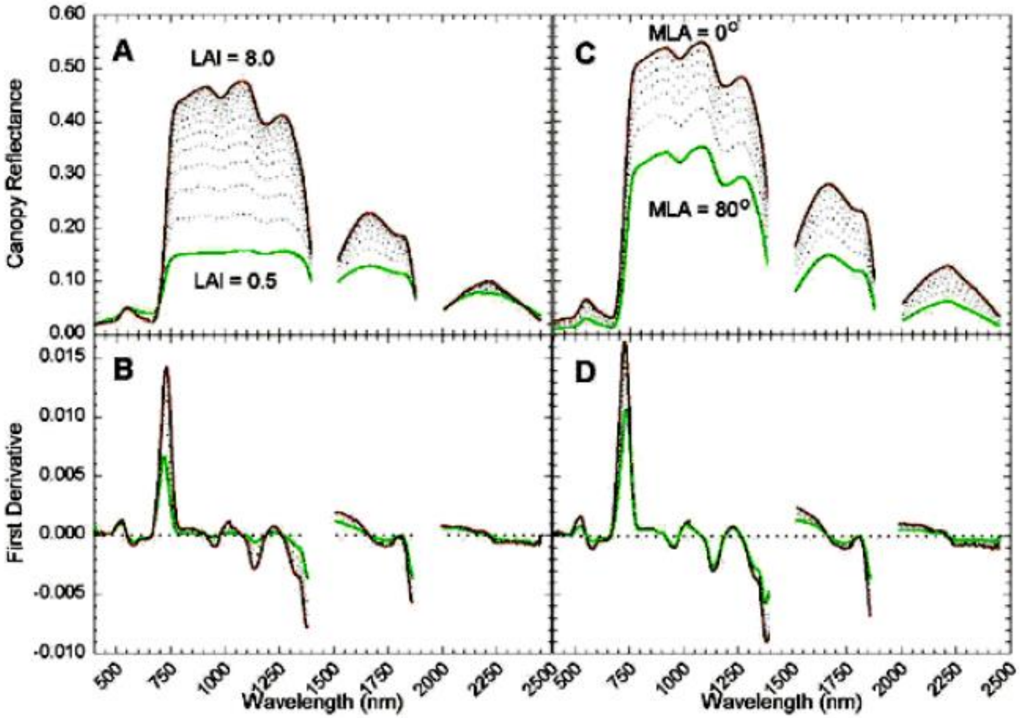
Vegetation

- Planophile Vs. Erectophile



- Leaf angle (towards nadir)





Asner, 1998

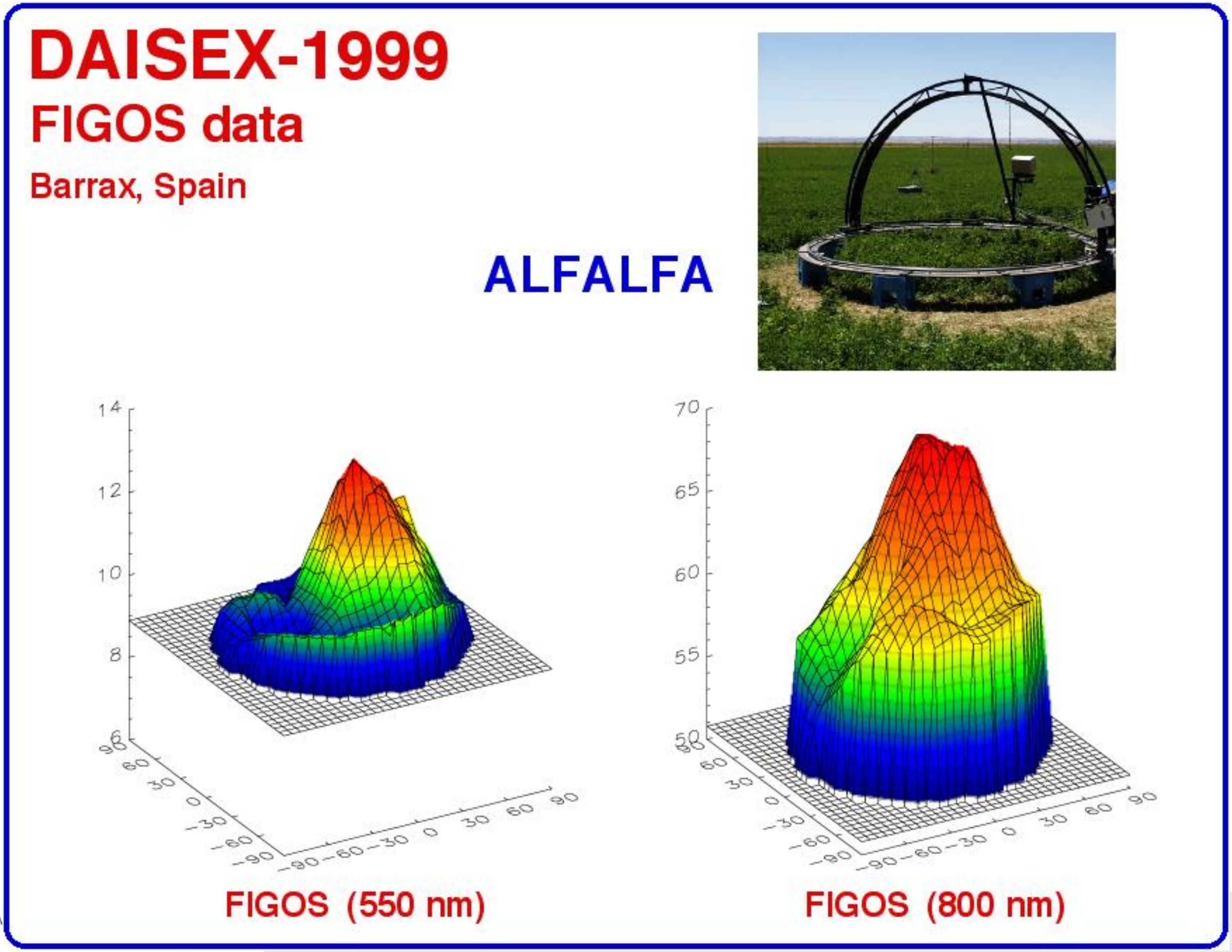
MLA: mean leaf angle

Vegetation

- LAI & NDVI:
  - NDVI is only accurate for LAI < 2, because
    canopy reflection saturates in VIS at LAI values of ~2, in NIR at ~5
  - Bare soil (LAI = 0) reach NDVI values of 0.2 – 0.5
  - NDVI is also influenced by chlorophyll and water content, vegetation structure and cover-%, and background albedo (e.g. soil, litter)
  - Only rough linear relationship between NDVI and LAI
  - Nevertheless, (small-band) NDVI is still a suitable vegetation index

- LAI & RedEdge-Infliction:
  - Accurate up till LAI ~10
  - But: no general & simple model

Vegetation – BRDF Signatures



Vegetation

- Canopy reflectance is thus influenced by
  - LAI
  - Vegetation cover fraction
  - Background reflectance
  - Qualitative and quantitative species composition
  - Angular dependencies / BRDF

Vegetation

Why not classify vegetation species using only absorption bands?

- Vegetation contains a large number of biochemicals in low concentration (exception: chlorophyll, lignin, cellulose) => small & shallow absorption bands

- Similar biochemical constitutions for most plants

⇒ Spectral variability within one species (different plant status and canopy) may be larger than inter-species variability

Soil

Soil

- MUNSELL soil colour
- Topsoil Moisture
- Topsoil organic matter content (SOM)
- Texture
- Structure
- Iron Content
- Mineral Composition
- Type of clay minerals
- Surface conditions

Soil

1 High organic matter content
2 Low “ “ “
3 Iron-rich soil

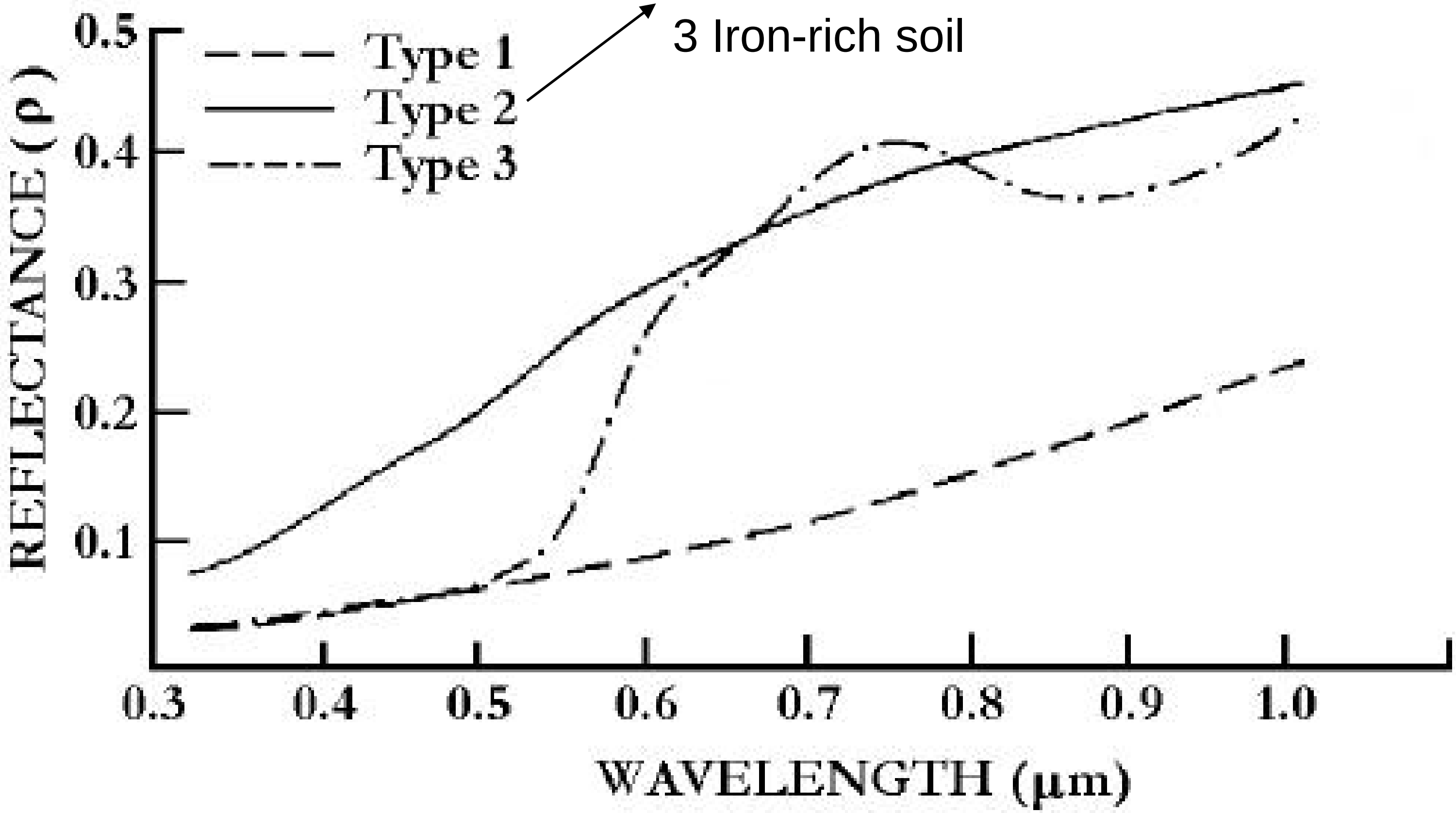


Figure 2-1: Classification of soil spectral curves into three general types according to CONDIT (1970, 1972) (from BAUMGARDNER ET AL., 1985; modified)

Soil

- SOM (Soil Organic Matter)
  - Decrease of ρ over whole wavelength range with increased SOM (if > 2.5% SOM)
  - shape-parameters in VIS:
    Correlation via 3rd order polynom between 0.35 & 1.4
    oder
    1st. Derivation (0.5-1.3): convex (<SOM) /
    concave (>SOM)

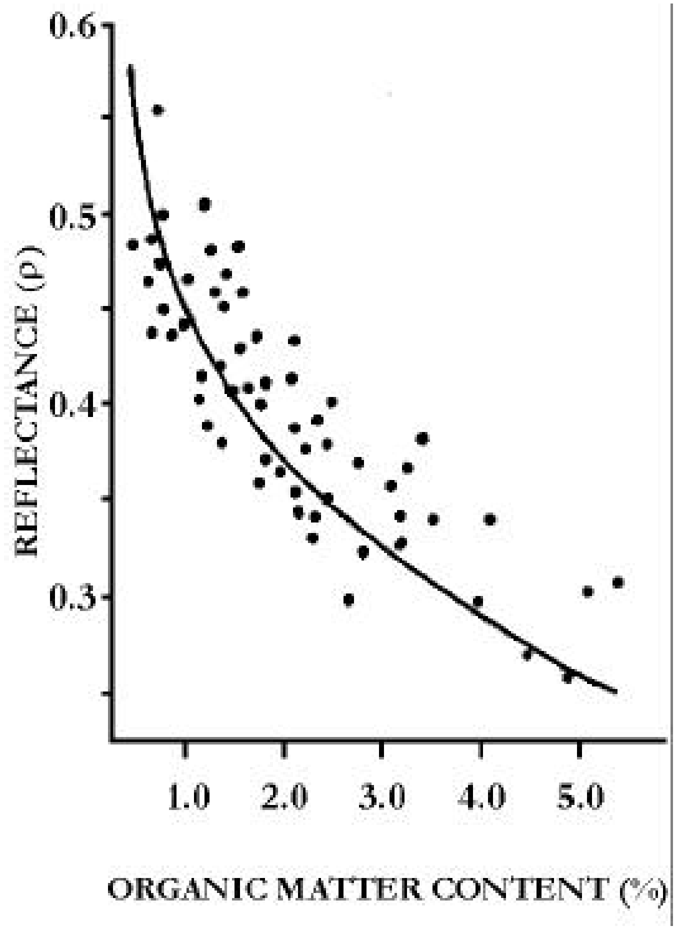
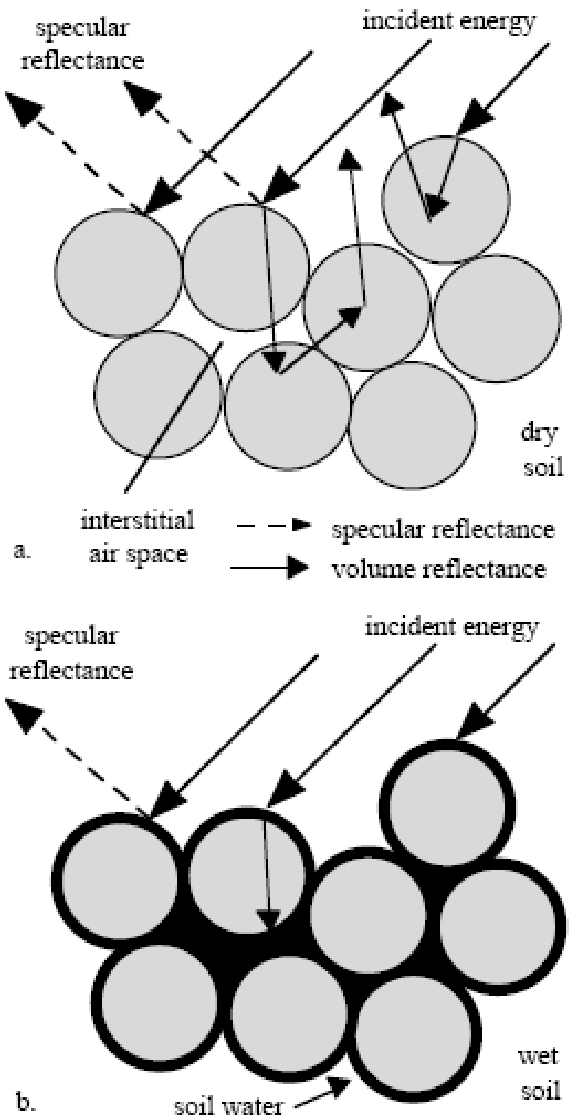


Figure 2-5 Experimental relation-ship between soil organic matter content and hemispherical reflectance in the visible wavelengths (modified from PAGE, 1974, in CURRAN, 1995)

Soil



Topsoil moisture

- ρ-decrease over whole wavelength range with increasing water content
- Main water & hydroxyl-features at 1.9 & 1.4
- Weaker features at 0.97, 1.20, 1.77
- Trapping effect in VIS:
  total reflection when transition from water
  to air

➔ more absorption by soil

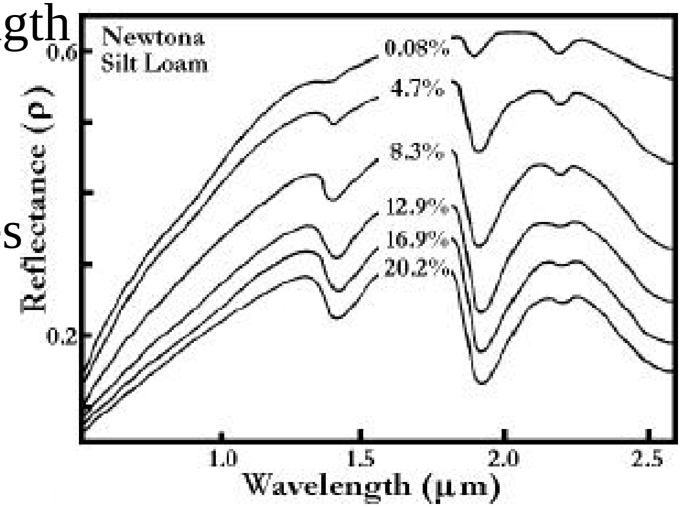


Figure 2-2: Effect of percent soil moisture content by weight on soil reflectance. Note that the ratio of moist soil reflectance to that of dry soil remains practically constant in large parts of the spectrum (IRONS, 1991; modified)

Soil

- Iron
  - Strong ρ decrease towards blue & UV
  - Hematite Fe_2O_3 0.86 µm
  - Goethite FeO(OH) 0.90 µm

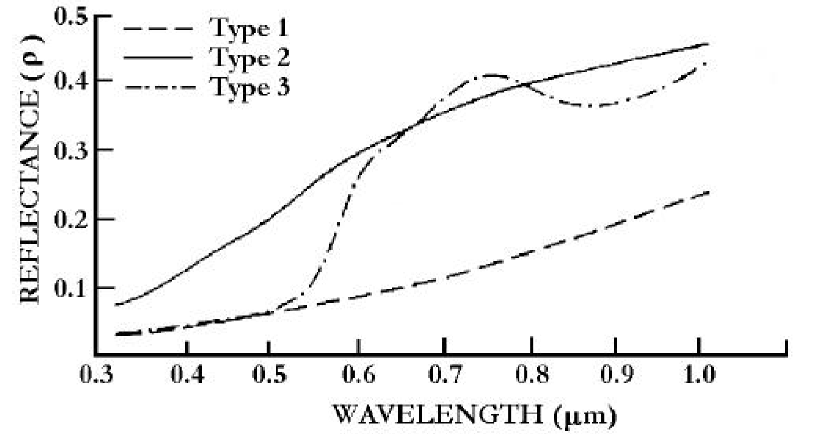


Figure 2-1: Classification of soil spectral curves into three general types according to CONDIT (19 1972) (from BAUMGARDNER ET AL., 1985; modified)

  - Iron hydroxides: most strongly increase from 0.55 to 0.59 µm
  - Hydrous Iron oxides most strongly increase from 0.5 to 0.54 µm
  - High overall iron content: broader feature at 0.87 µm

Soil

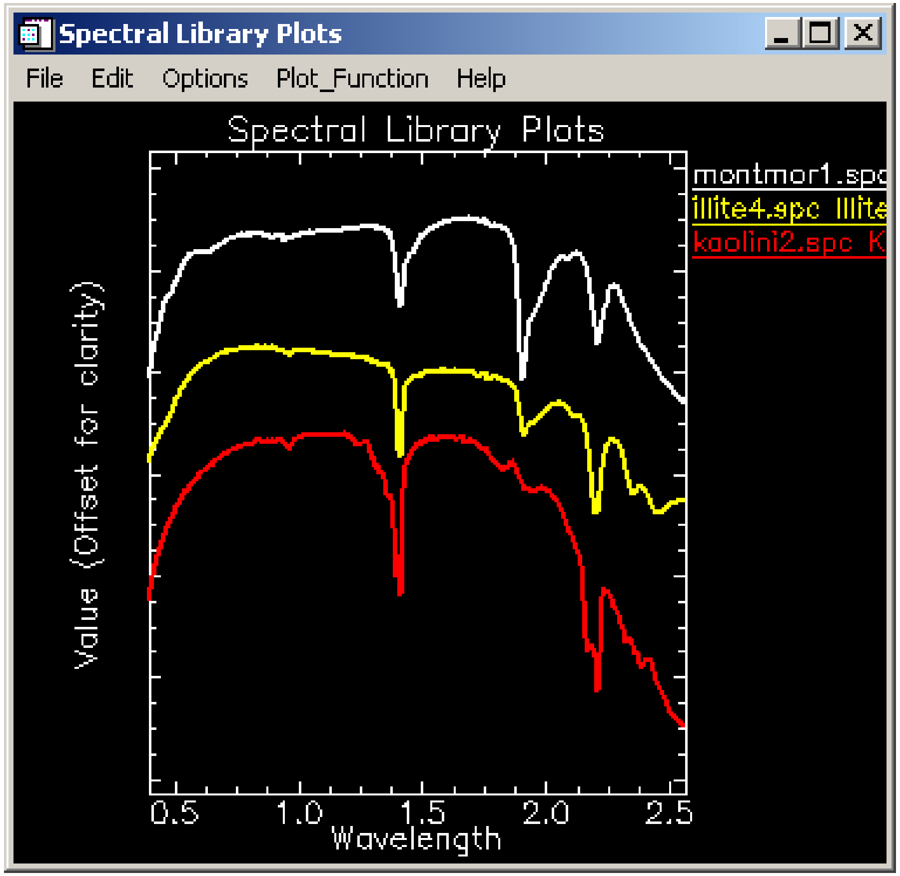
- Other soil mineral features
(not as easily distinguishable as rock to due to higher mixing)

  - Al-OH: 2.2 µm
  - MgOH: 2.3 µm
  - Carbonate: 2.16 & 2.35 µm
  - Gipsum: 1.75 & 2.2 µm => also indicator for soil salinization
  - Clay minerals: 2.2 µm => also for nutrient content

- Influence of soil texture:
finer particles => increased reflection & less multiple scattering => less contact with material => lesser contrast of absorption features

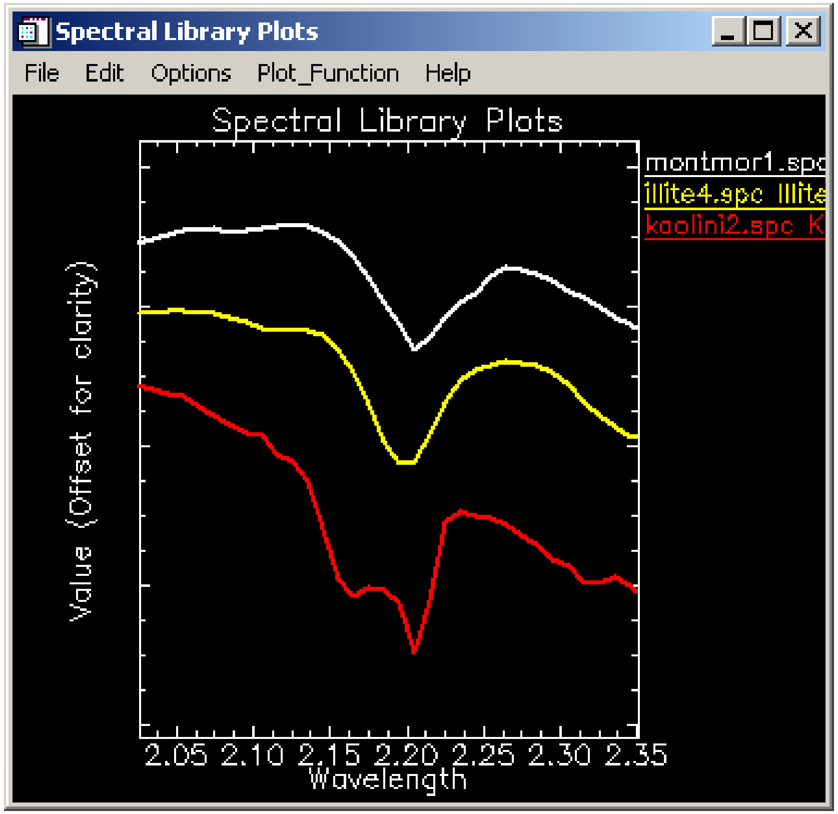
Soil

- Soil mineral composition
  - Neither Si, Al, or O have diagnostic features in VNIR
  - Gypsum 1.8 & 2.3 μm
  - Carbonates 1.75, 2.16, ~2.30 μm
  - Salt: >ρ between 0.52 – 0.90 μm
  - Clay Minerals near 2.2 μm due to hydroxyl-ions
    - Montmorillonite: strong at 1.4 μm and 1.9 μm (bound water)
    - Kaolinte: strong at 1.4 μm and doublet feature at 2.2 μm (OH)



Soil

- Expansive soils (swelling clays)
  - Montmotillonite swells up to 15 times its volume when water is present
  - Some soils swell up to 1.5 times their volume
  - ➔ Detection of Montmotillonite, Bentonite & Smectite



Soil

- Particle size

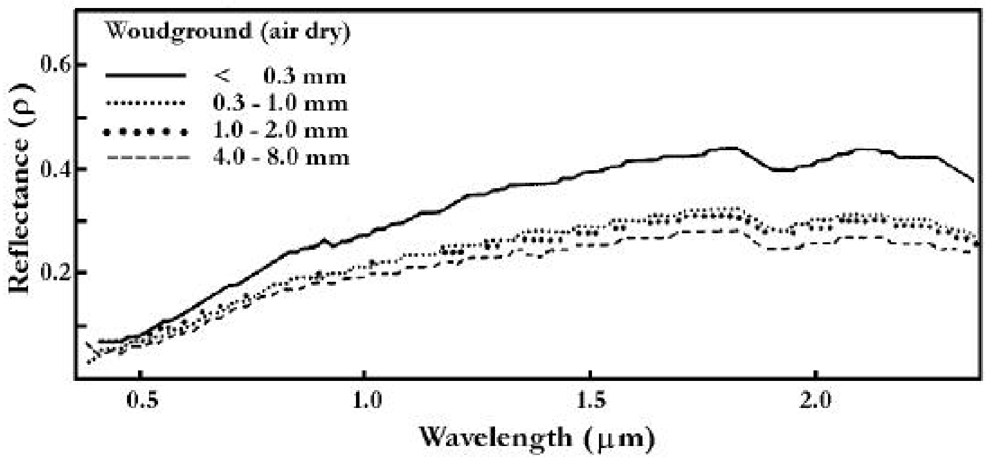


Figure 2-9: Spectral soil reflectance for different aggregate diameters (MULDERS, 1987)

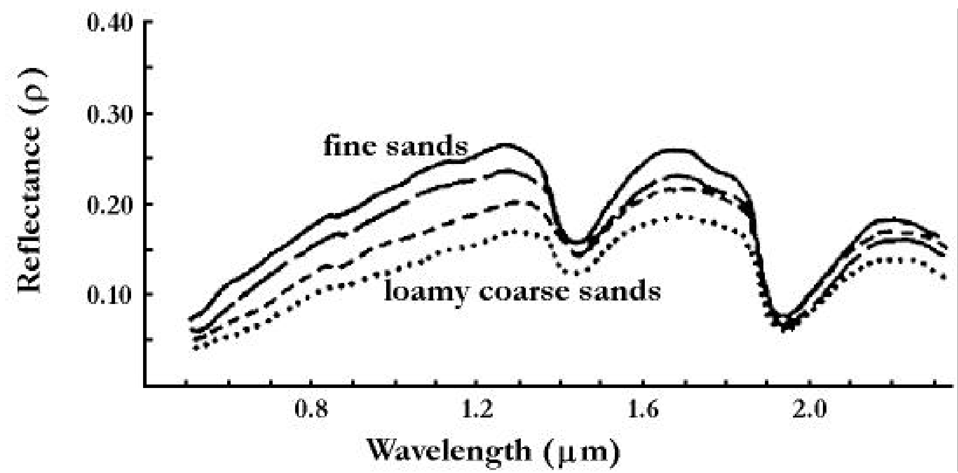


Figure 2-8: Influence of predominant particle size on bare soil reflectance. Soil texture varies from fine sands (top), fine loamy sands, loamy sands, to loamy coarse sands (bottom) (BAUMGARDNER ET AL., 1985)

< particle size ➔ >ρ at all λ & decreases contrast of spectral features

Exception: clay ➔ larger aggregates!

Soil

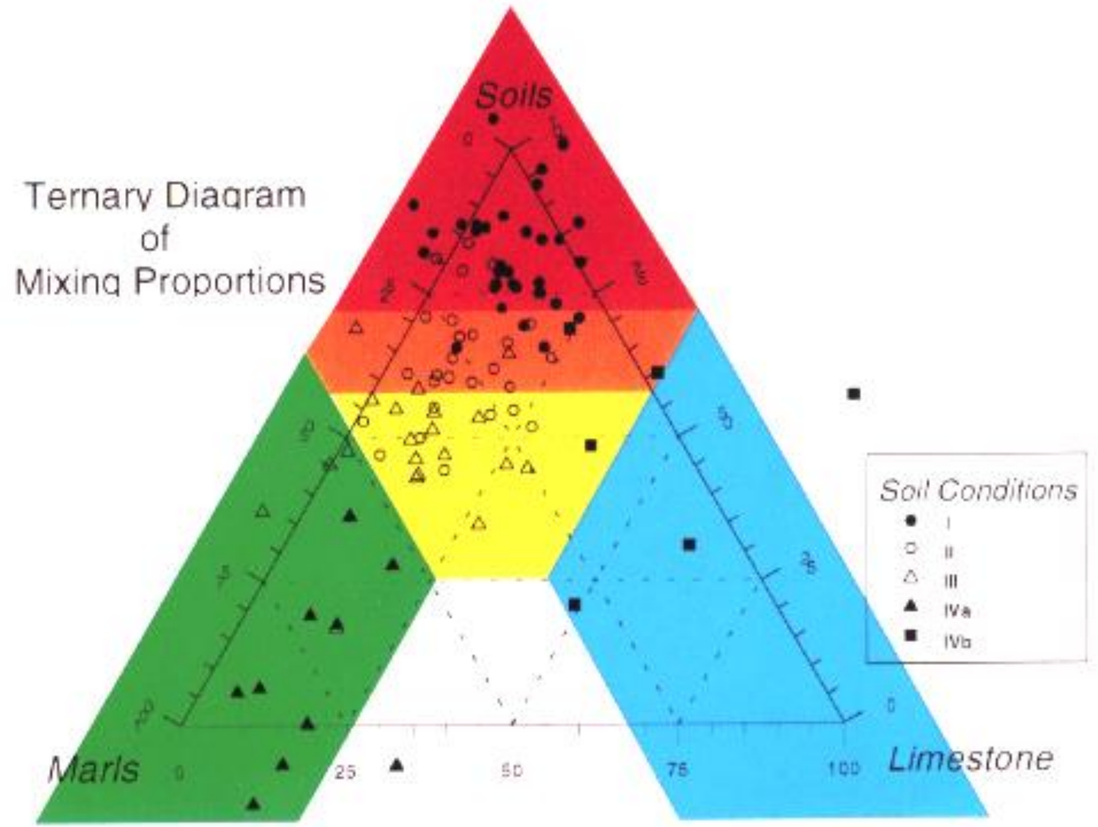
- Soil BRDF
  - Sandy soils: almost equally distributed, slightly higher reflection in illumination direction
  - Clayish soils: highly irregular due to clay aggregates

Soil

- Physical soil condition
  - Tillage ➔ >scattering, >shade
  - Physical crusts & Smooth surface ➔ generally >ρ
  - Biogene surface crusts
  - Litter
  - …

Soil

- Soil degradation
  - Scheme of degradation state by HILL



Geology

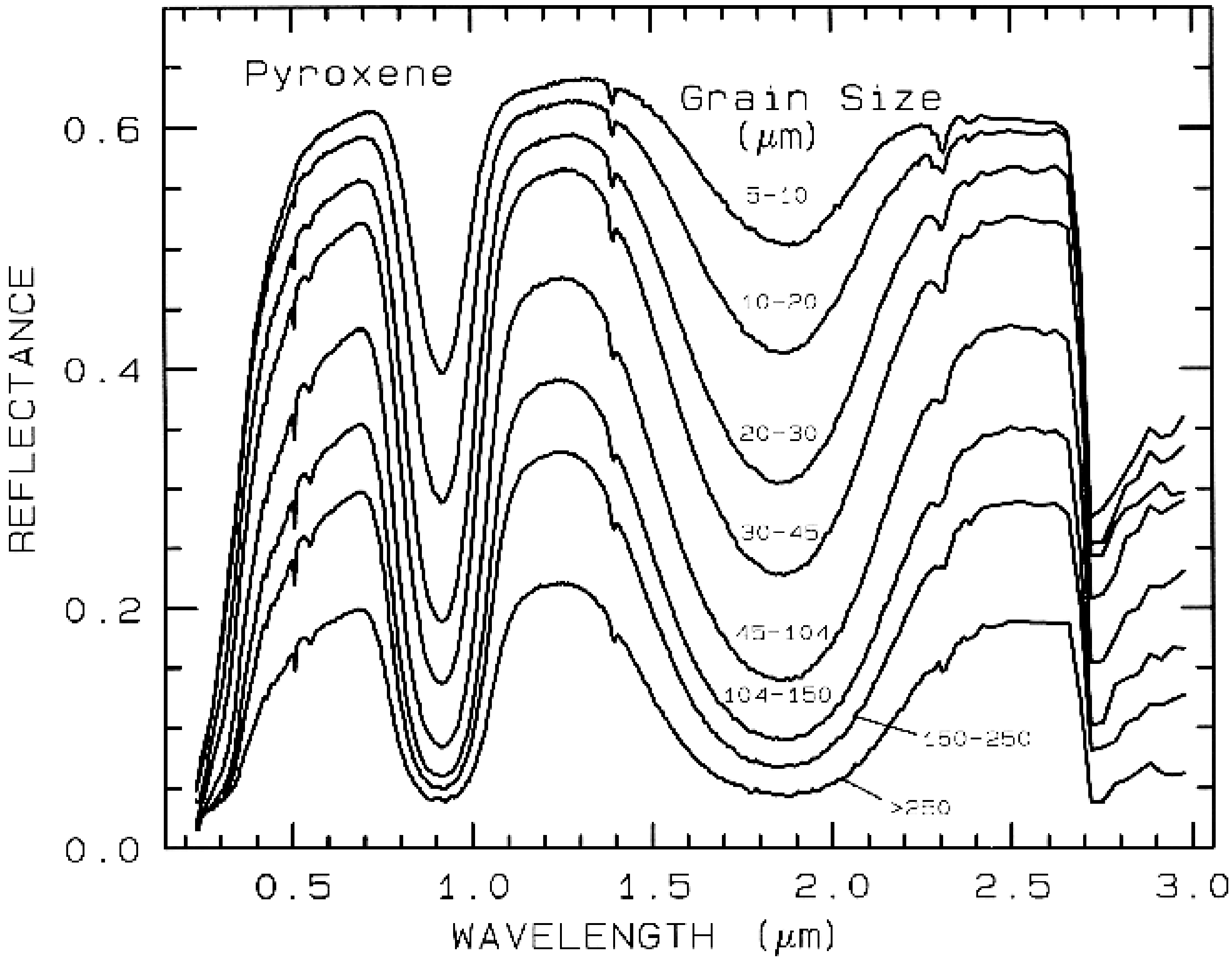
Geology

- Calcites 1.76 & 1.80 µm
- Dolomites 1.74 & 1.86 µm
- Both at ~2.3 µm

- Iron
  - Strong ρ decrease towards blue & UV
  - Hematite Fe_2O_3 0.86 µm (iron (III) oxide)
  - Goethite FeO(OH) 0.90 µm (iron hydroxide)

  - Iron hydroxides: most strongly increase from 0.55 to 0.59 µm
  - Hydrous Iron oxides most strongly increase from 0.5 to 0.54 µm
  - High overall iron content: broader feature at 0.87 µm

Geology



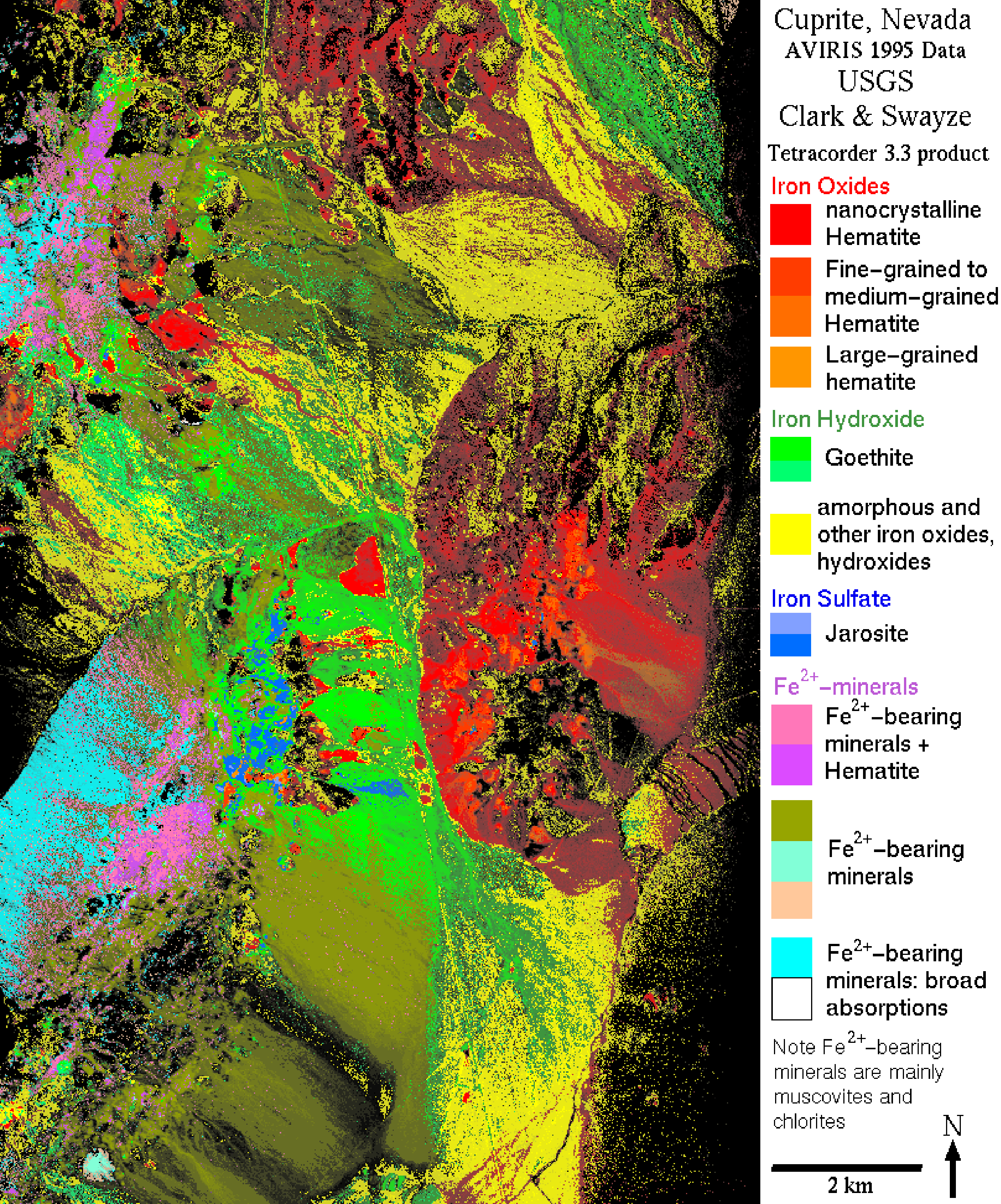
Rule of thumb:
Smaller grains
➔ more scattering
➔ less prominent features

Geology

Hapke's equation to model the reflectance (r_λ) from an *exposed* rock

$$r_\lambda = \left[\frac{w'}{4\pi} \times \frac{\mu}{\mu + \mu_0} \right] \times [(1 + B_g) P_g + H_\mu H_{\mu_0}^{-1}]$$

μ_0=cosine of angle of incident light, μ=cosine of angle of emitted light, g=phase angle, w'=average scattering albedo from rock or mineral, B_g=backscatter function, P_g=average single particle phase function, H=function for isotropic scatterers.

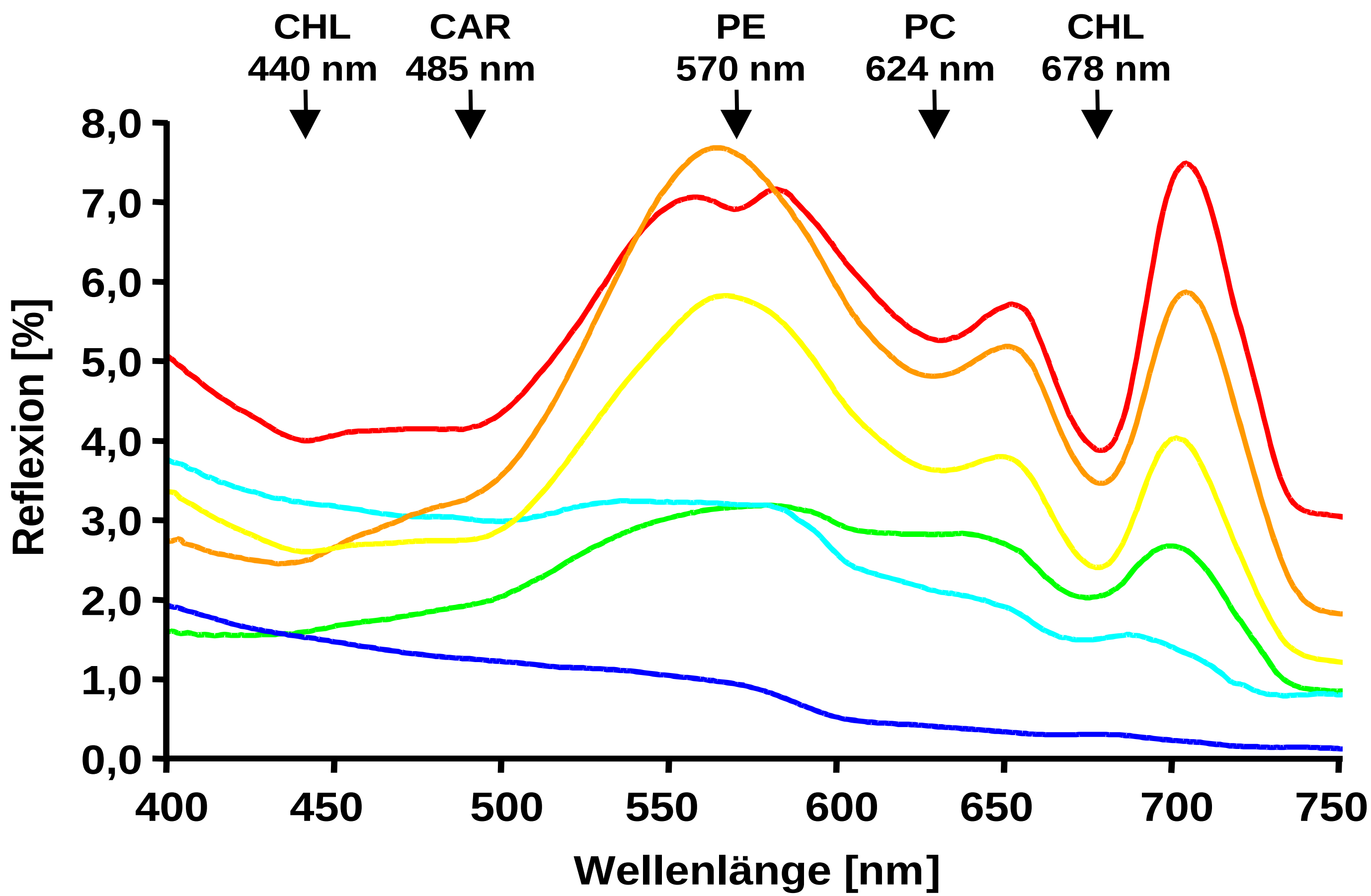

Cuprite, Nevada
AVIRIS 1995 Data
USGS
Clark & Swayze
Tetracorder 3.3 product
Iron Oxides
nanocrystalline Hematite
Fine-grained to medium-grained Hematite
Large-grained hematite
Iron Hydroxide
Goethite
amorphous and other iron oxides, hydroxides
Iron Sulfate
Jarosite
Fe^{2+}-minerals
Fe^{2+}-bearing minerals + Hematite
Fe^{2+}-bearing minerals
Fe^{2+}-bearing minerals: broad absorptions
Note Fe^{2+}-bearing minerals are mainly muscovites and chlorites
N
2 km

Hydrological Applications

Water

Objective	spectral range	spectral resolution
	VIS: 400 – 700 nm:	
"yellow substance"	410 – 420 nm	20 nm
chlorophyll absorption	445 nm	10 nm
high chlorophyll pigments	495 nm	10 nm
anorganic suspended sediments		
sediments	520 & 620 nm	10 nm
chlorophyll reflexion-max.	565 nm	"
" absorption	670 nm	"
chlorophyll fluorescence max.	685 nm	5 nm
	NIR: 700 - 1400 nm	

Spectral signatures of lakes



1 – *Großer Wummsee* (25.9.'97): 2 µg/l Chl-a
2 – *Schwarzer See* (11. 6.'97): 11 µg/l Chl-a
3 – *Kagarsee* (11.6.'97): 34 µg/l Chl-a
4 – *Braminsee* (25.9.'97): 48 µg/l Chl-a
5 – *Braminsee* (2.9.'97): 70 µg/l Chl-a
6 – *Braminsee* (10.6.'97): 90 µg/l Chl-a

Messkampagne Starnberger See 14.5.2012

Teilnehmer: OpAiRS-Team + MF-GW + TUM

Bestimmung der Tauchtiefe des Sonars

Messung von Parametern der Atmosphäre

Befliegung mit HySpex

Optische Eigenschaften des Wassers,
Konzentrationen von Wasserinhaltsstoffen

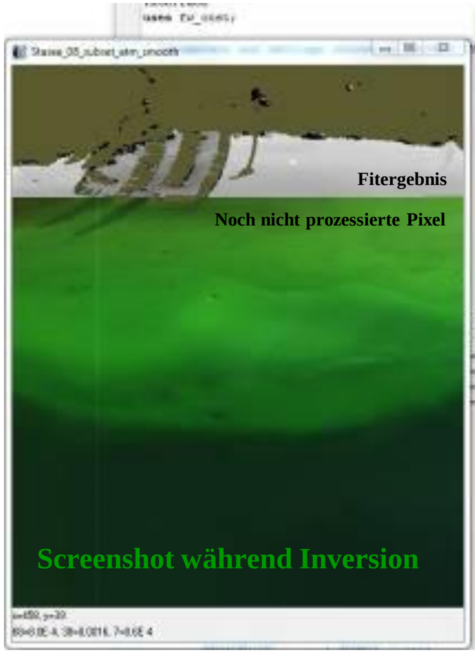
Wassertiefe

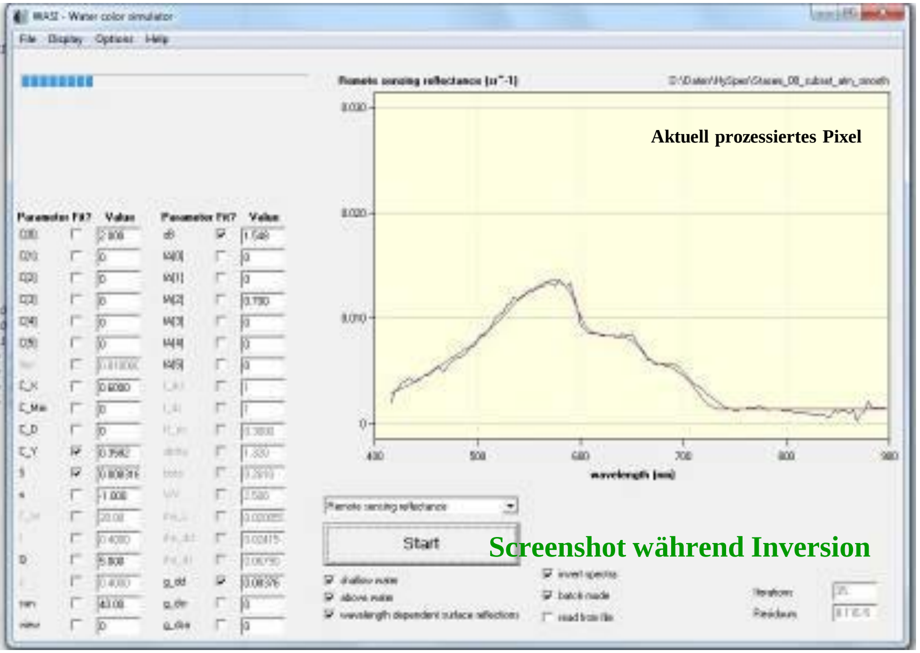
Unterwasser-Spektrometer

Weisse Folie am Grund

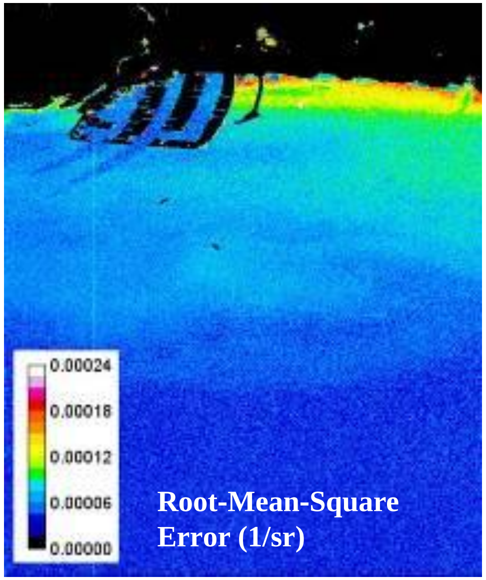
Messkampagne Starnberger See 14.5.2012

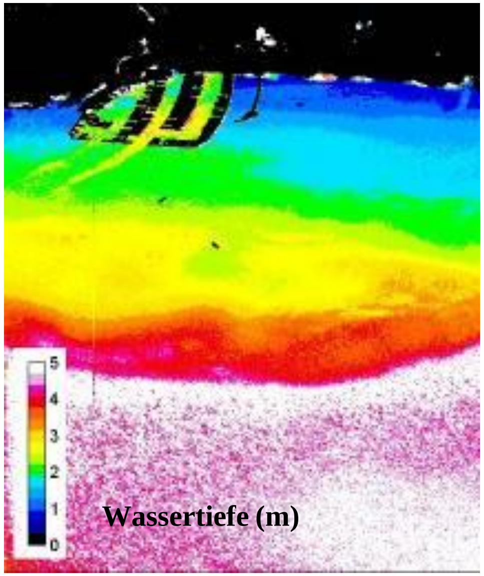
Erste Ergebnisse mit WASI-2D (Atmosphärenkorrektur mit ATCOR)

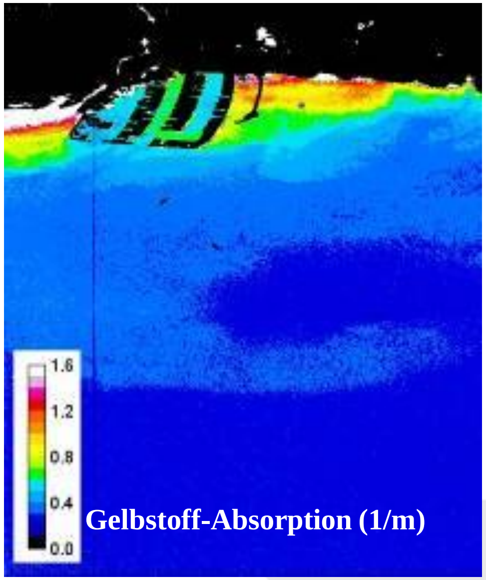


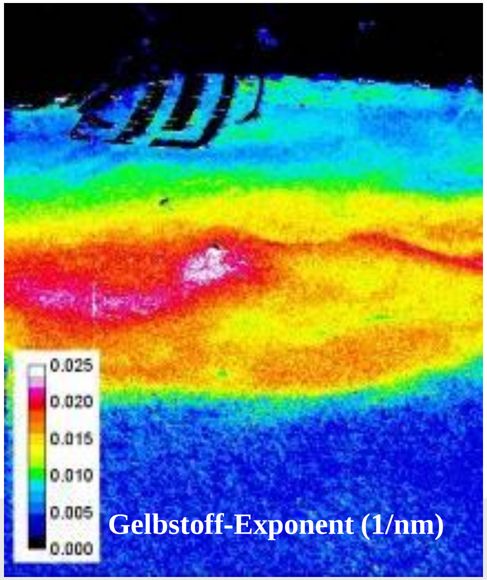


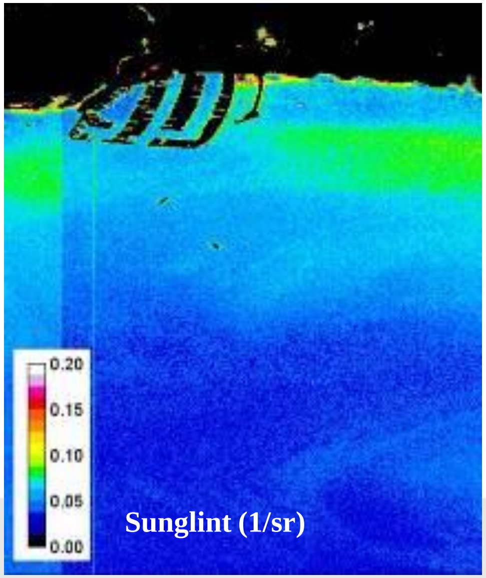
Befliegung mit HySpex











Water

Estimation of snow grain size: