Produkční biologie Bi8030
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Optical properties of leaves and its implication in understanding plants functional properties and primary production

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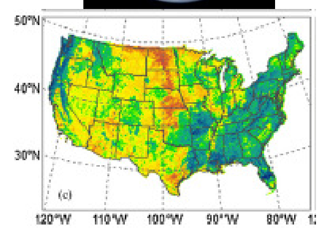
Spatial Scales of Inquiry:
Span 13-14 orders of Magnitude

Globe: 10,000 km (10^7 m)



Continent: 1000 km (10^6 m)

Landscape: 1-100 km

Canopy: 100-1000 m

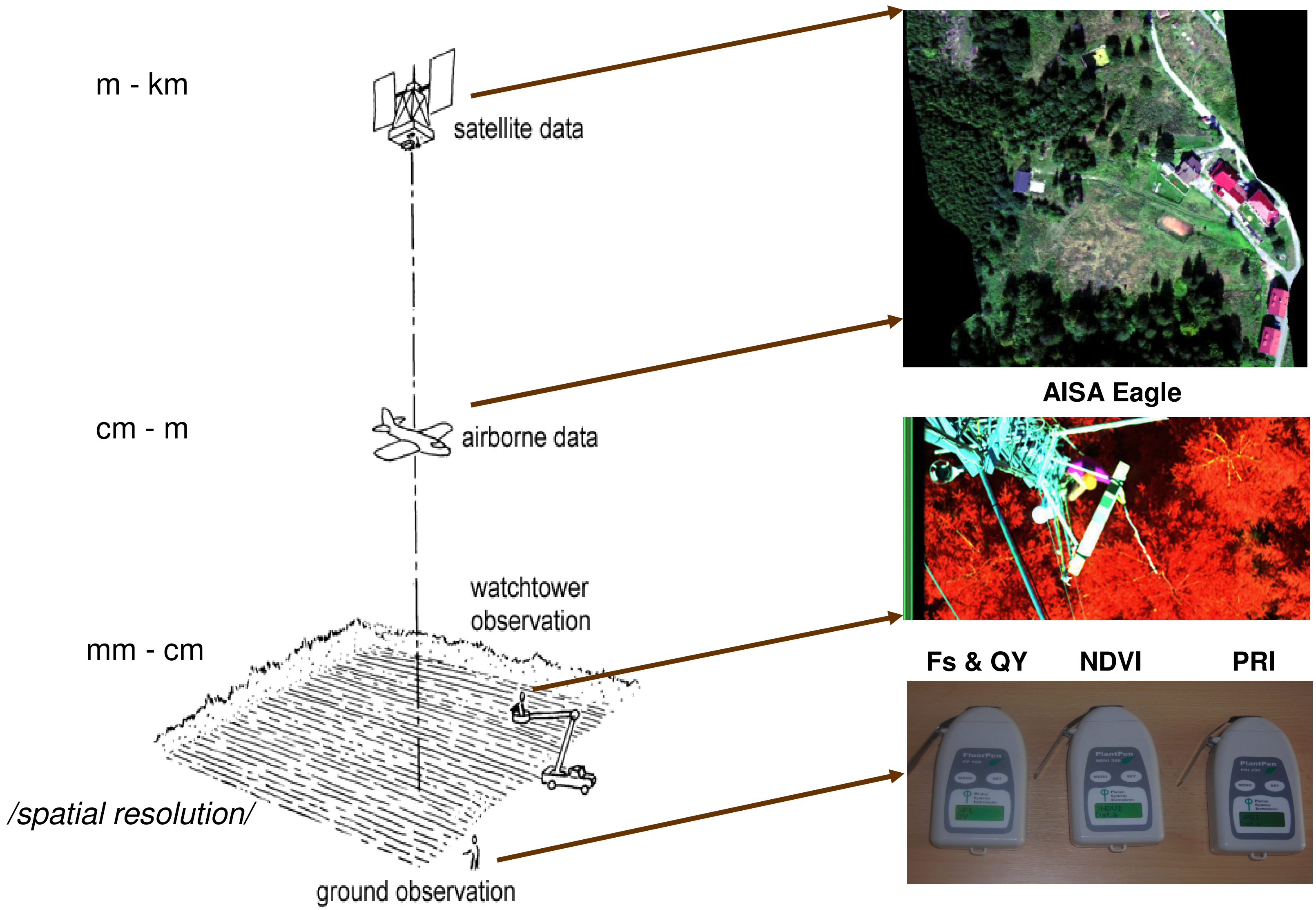
Plant: 1-10 m

Leaf: 0.01-0.1 m

Stomata: 10^{-5} m

Bacteria/Chloroplast: 10^{-6} m

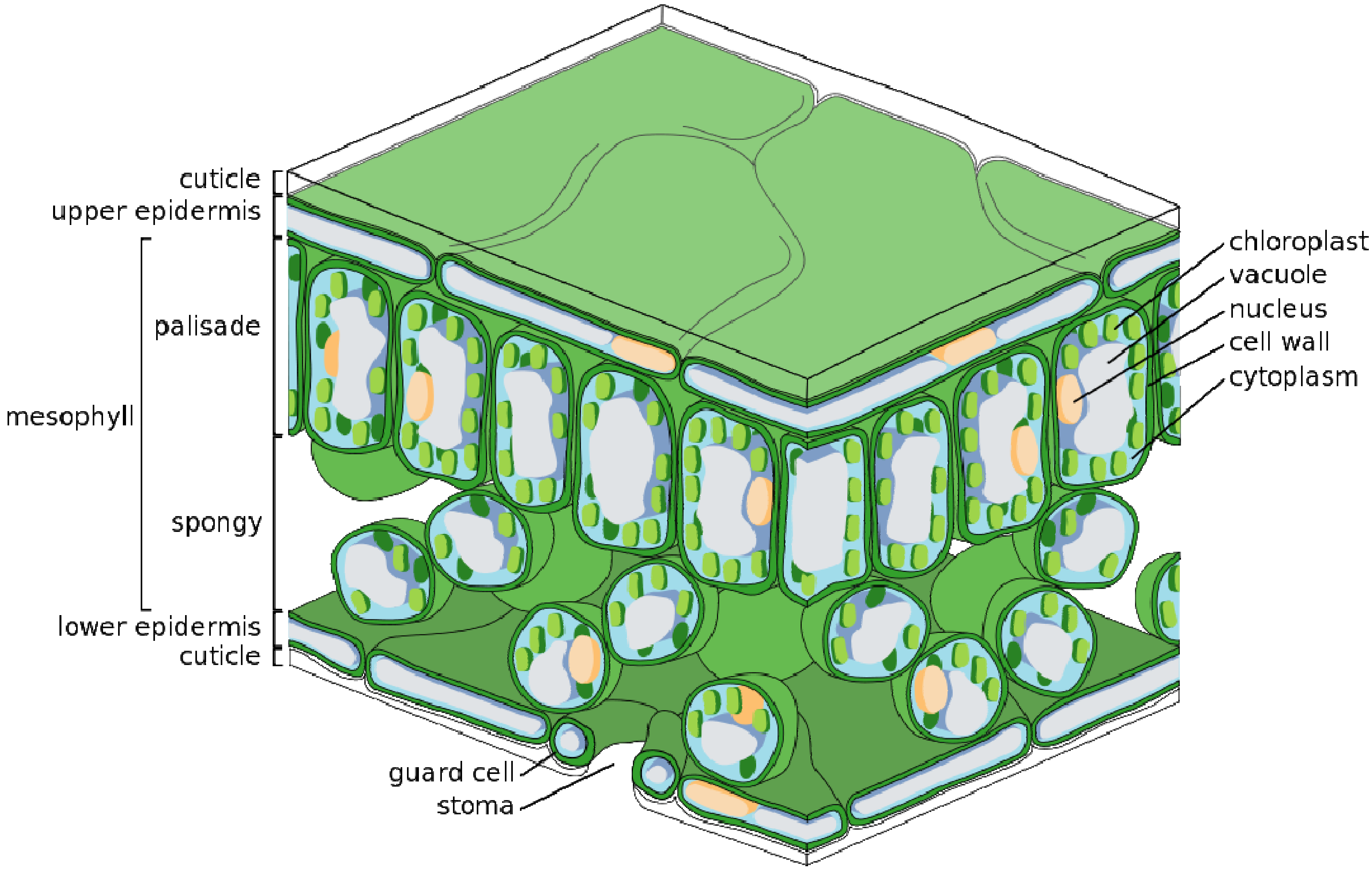
Multi-scale monitoring



Plant leaves and its function

- Producing food and oxygen through photosynthesis
- Balancing water loss
- Regulating gas exchange
- Transporting products of photosynthesis

Diagram of the internal structure of a leaf



Cross section of leaves

Cuticle:

Upper epidermis:

Preventing water loss, providing an extra layer between the outside and inside of the leaf.

Mesophyll.

-palisade layer

Chloroplast; **photosynthesis, food & O_2**

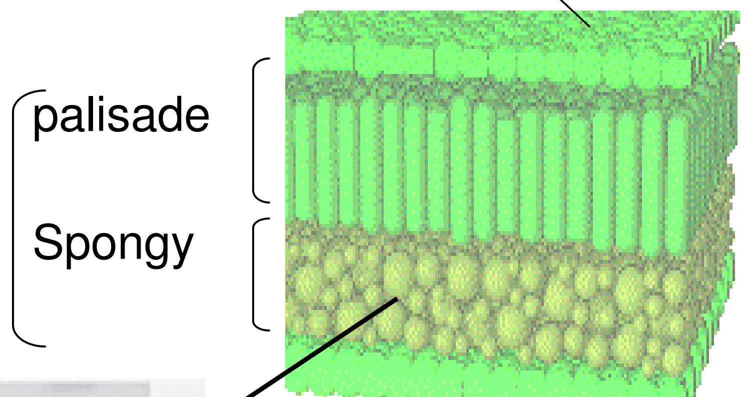
-spongy layer

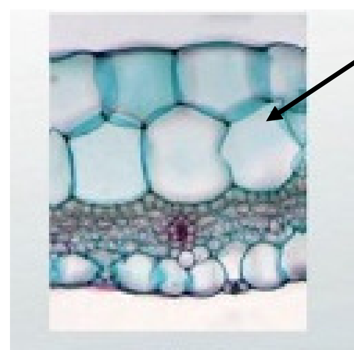
vascular bundles: xylem and phloem

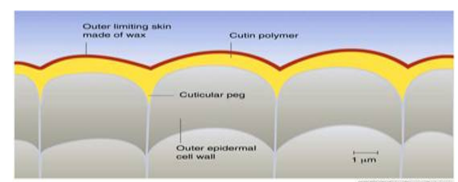
Lower Epidermis

Stomata

Upper cuticle







Leaves: Cuticle & Epidermis

Waxy layer: (hydrophobic)

-prevent water loss,

-first defense against pests and pathogen

-reflect UV light

-self cleaning (Lotus)-

Deposition of pathogens

Sunlight blocking particles

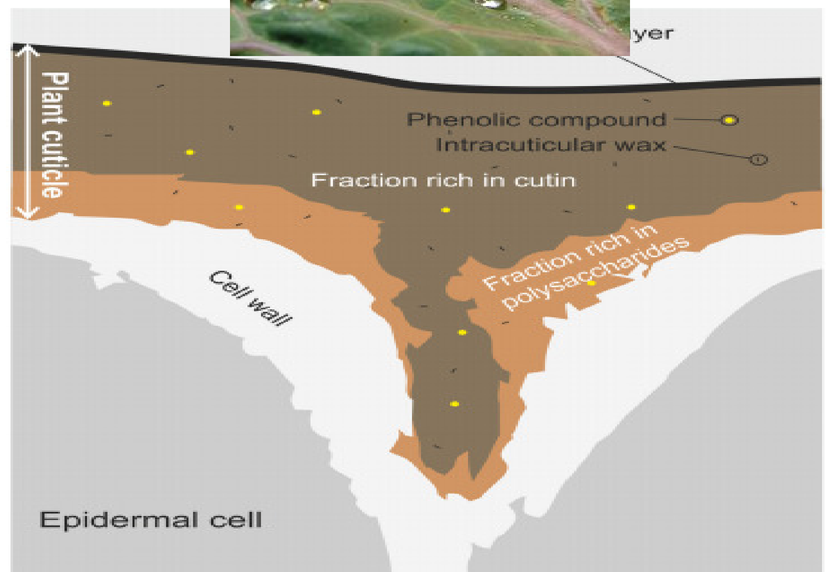
Phenolics:

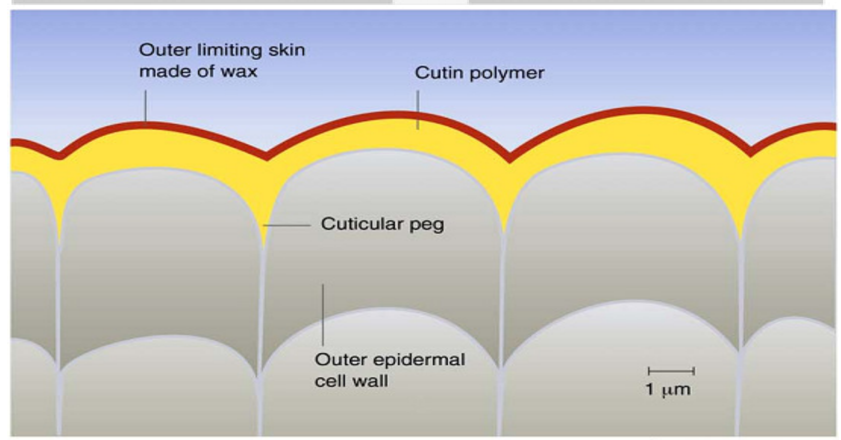
-UV screening,

-Antioxidant,

-changes with environment, stresses

Heredia-Guerrero et al.(2014)





TRENDS in Plant Science

Localization of different subgroups of phenolics at tissues and cellular level

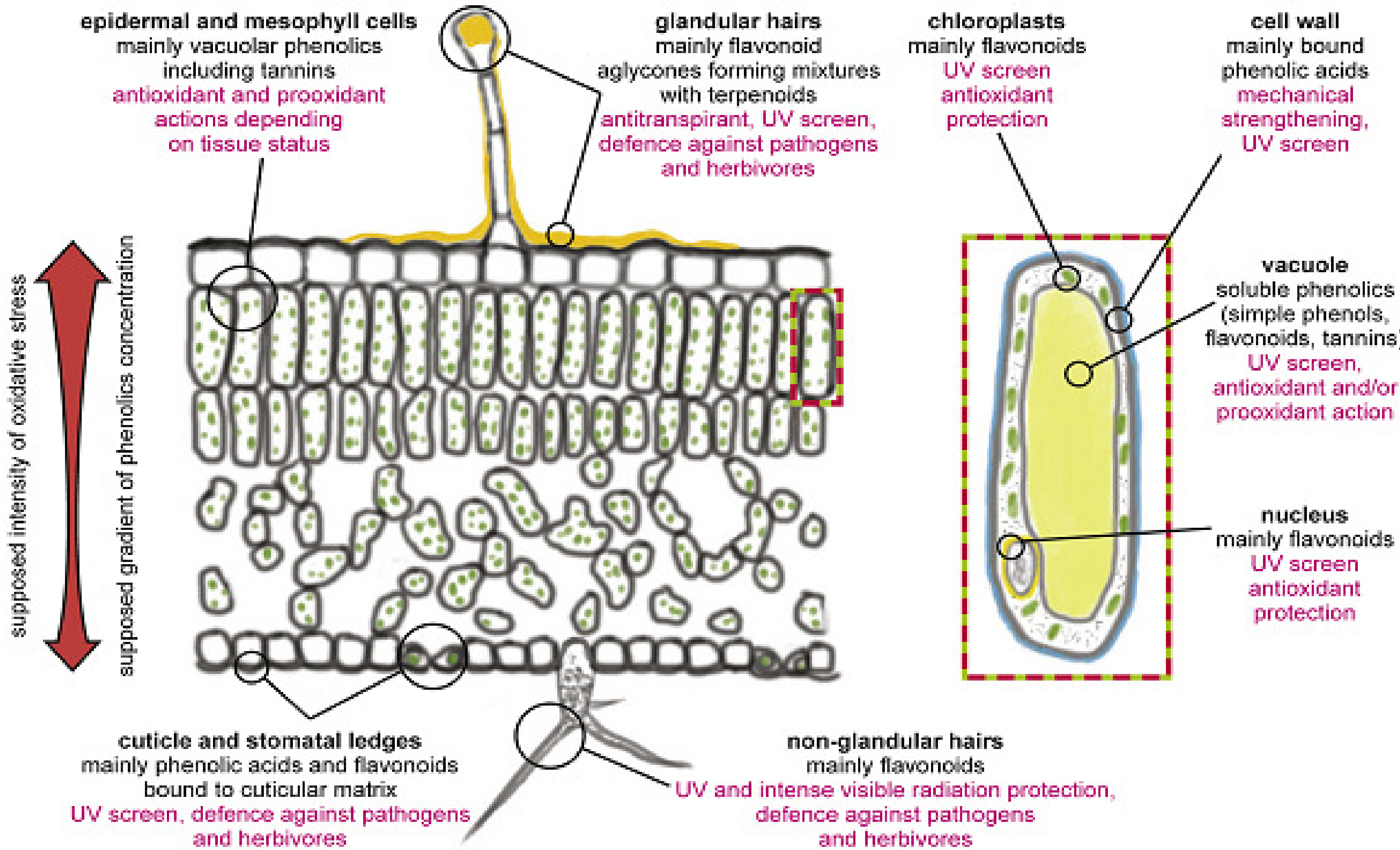


Fig. 2. Schematic representation of typical anatomical features, often occurring in hypostomatic leaves, showing the localization of the different subgroups of phenolics at tissue and cellular level. The main roles of phenolics of each feature are shown in magenta. Two-headed arrow shows the hypothetical gradient of oxidative stress and hypothetical concentration of phenolic compounds across mesophyll tissues. For details, see text.

Karabourniotis et al. (2014) Plant Science 227:21-27

Spectral regions of absorption maxima of compounds in leaves epidermis

Table 1. Spectral regions of absorption maxima of major classes of phenolics (aglycones in methanol). Compiled from Jurd (1957), Harborne (1989), Mabry, Markham & Thomas 1970) and from our own measurements. In most cases, glycosylation of these compounds shifts the Band I maximum towards shorter wavelength

UV-absorbing compound	Absorption maxima (nm)								
Simple phenols			266–295						
Phenolic acids		235–305							
Hydroxycinnamic acids[a]	227–245				310–332				
Chlorogenic acid	244				329[b]				
Caffeic acid	244				324[b]				
Ferulic acid	234				320[b]				
Sinapic acid	235				319				
Stilbenes				300–310	320–330				
Spectral bands[d]	**240**	**260**	**280**	**300**	**320**	**340**	**360**	**380**	**Vis[a]**

[a]The spectral data for hydroxycinnamic acids are given for the E- (*trans*-) isoform of the acids, which is preponderant *in vivo*.
[b]Chlorogenic, caffeic and ferulic acid have a pronounced shoulder (inflection) at 299 nm.
[c]For isoflavones and flavanones band I is a minor band; it is of a much smaller amplitude than band II, or the band I of flavones or flavonols.
[d]The UV region is divided into 20-nm-wide spectral bands with the central wavelength indicated (Vis, visible).

Cerovic et al.(2002) Plant Cell and Environment, 25: 1663-1676

Spectral regions of absorption maxima of compounds in leaves epidermis

Flavonoids		Band II (benzoyl)				Band I (hydroxycinnamoyl)			
Isoflavones		255–265			(310–330)[c]				
Flavanones			275–290		(310–330)[c]				
Flavones3		250–270				30–350			
Apigenin		267				336			
Luteolin		267				349			
Flavonols		250–270					350–390		
Kaempferol		266					367		
Quercetin		255					370		
Chalcones		240–260						365–390	
Aurones3		240–270							390–430
Anthocyanins		267–275							475–545
Spectral bands[d]	**240**	**260**	**280**	**300**	**320**	**340**	**360**	**380**	**Vis**[a]

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Cerovic et al.(2002) Plant Cell and Environment, 25: 1663-1676

How to measure compounds in the Leaf epidermis?

-Extraction of leaf cuticle and measurements of absorbance and transmittance

Krauss et al. (1997) Plant, Cell, and Environment 1997

Problems in measuring epidermis contents by leaf extraction:
leaf structures on UV absorption, and the local distribution of phenylpropanoids in leaves are lost by the extraction procedures.

ChlF excitation ratio (FER) = ChlF yields [UV / blue-green excitations]

Log(FER)= absorbance of leaf epidermal

Cerovic et al.(2002) Plant Cell and Environment, 25: 1663-1676

How to measure compounds in the cuticle?

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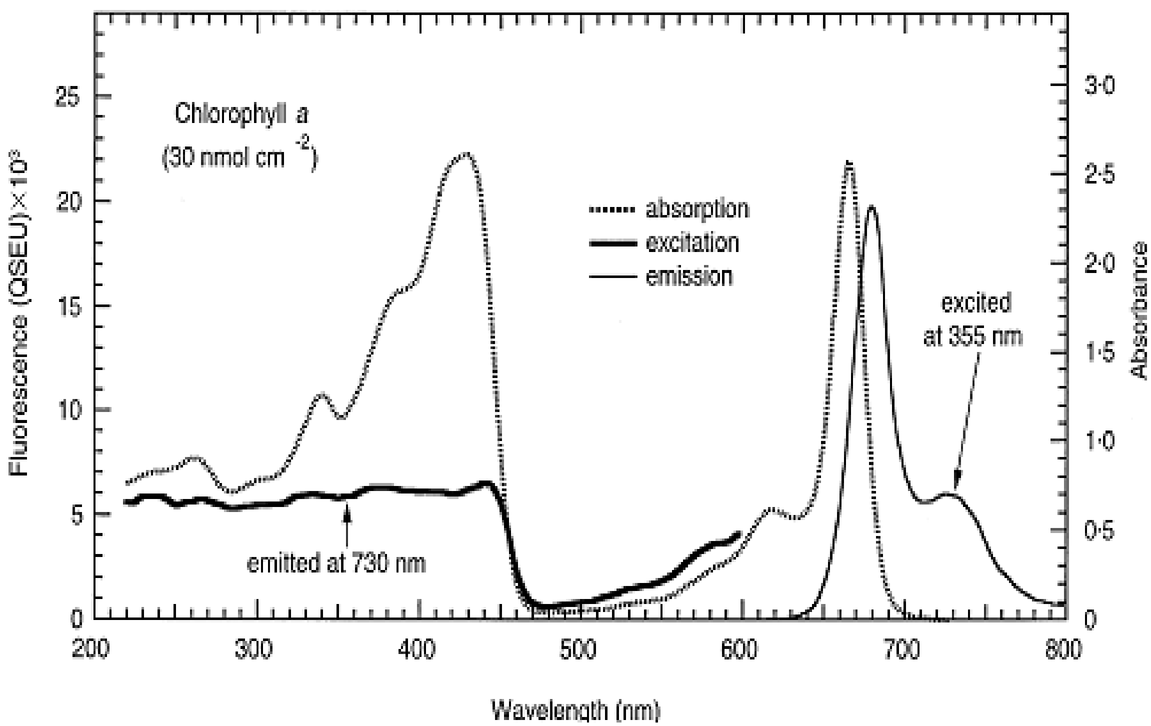
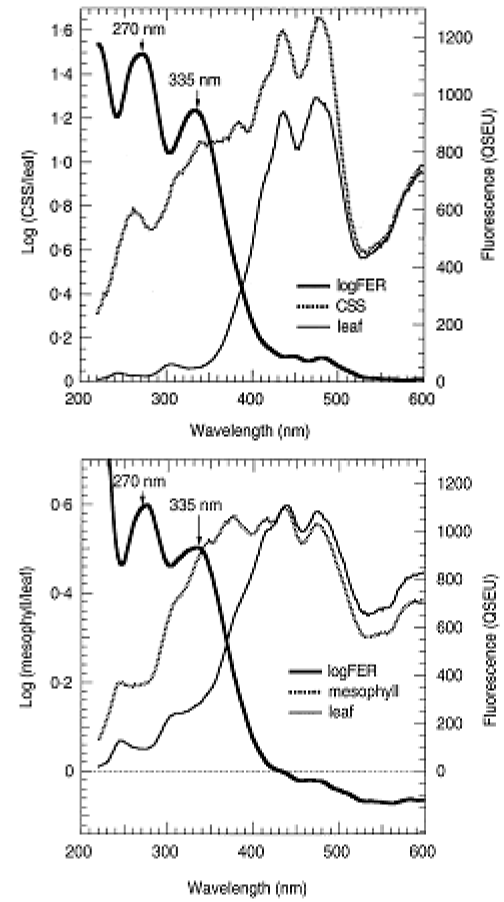
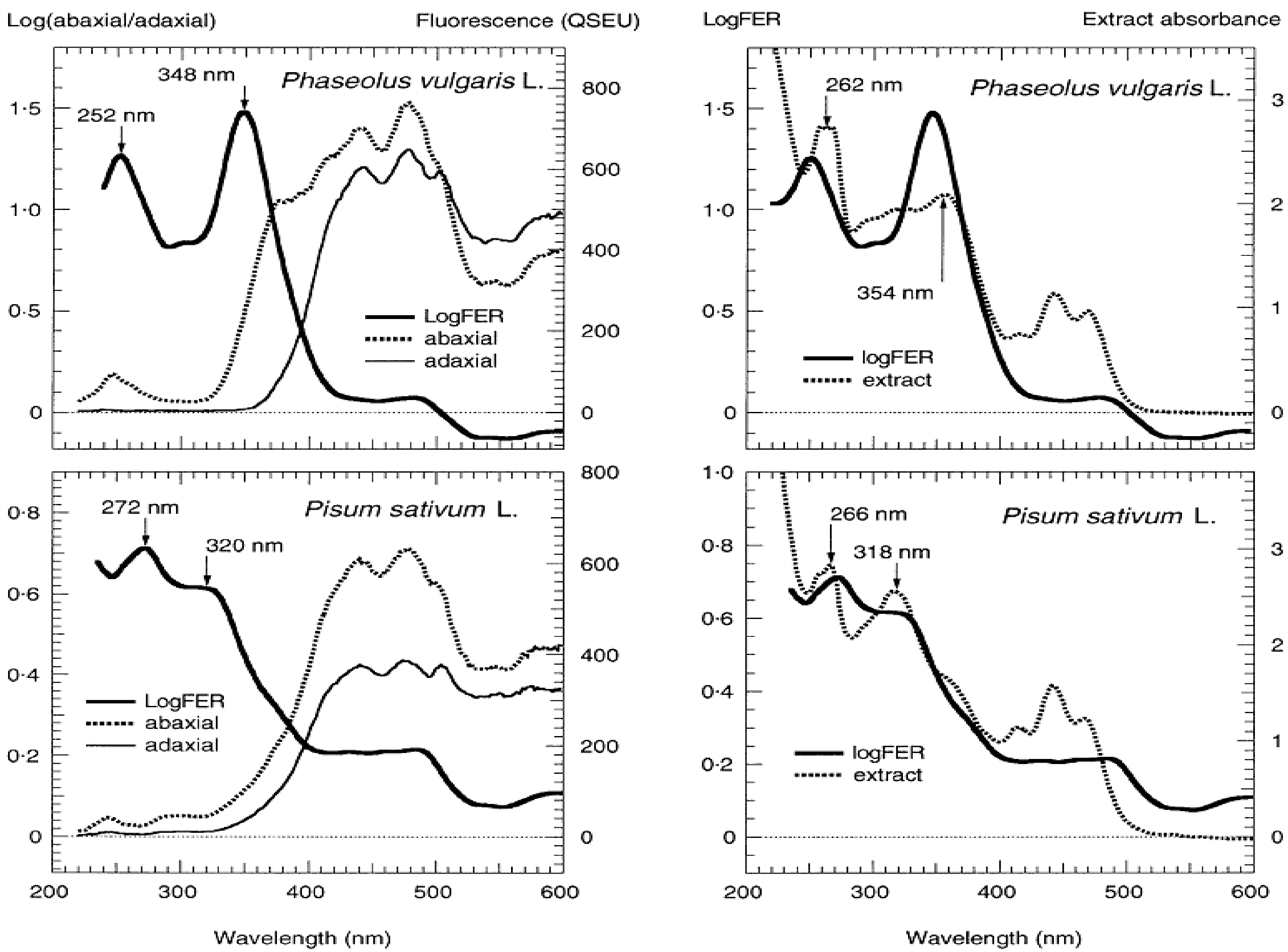




Cerovic et al.(2002) Plant Cell and Environment, 25: 1663-1676

FER can measure absorbance of leaf epidermis

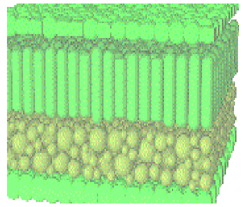


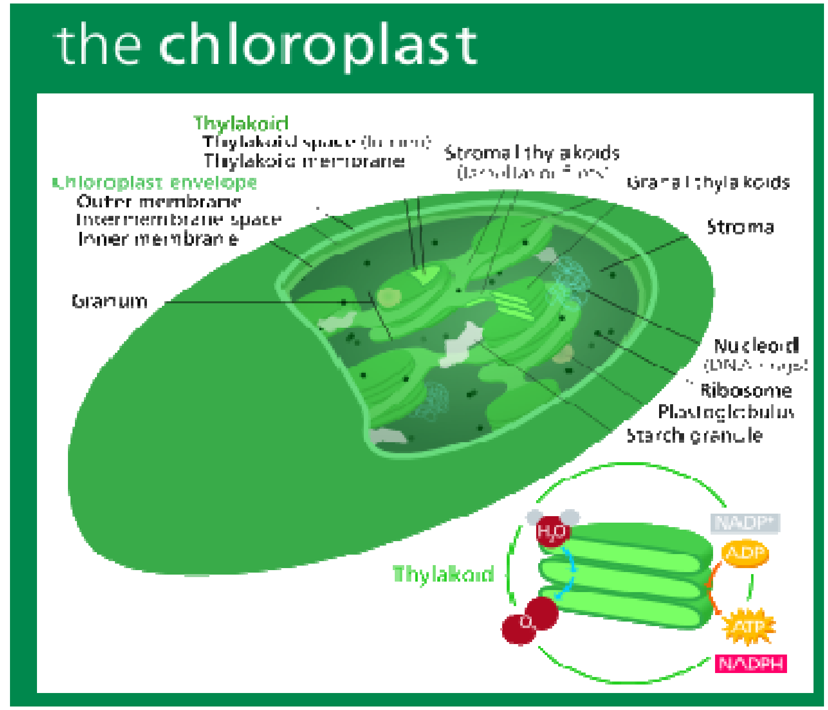
Cerovic et al.(2002) Plant Cell and Environment, 25: 1663-1676

Leaves: Mesophyll & Lower Epidermis

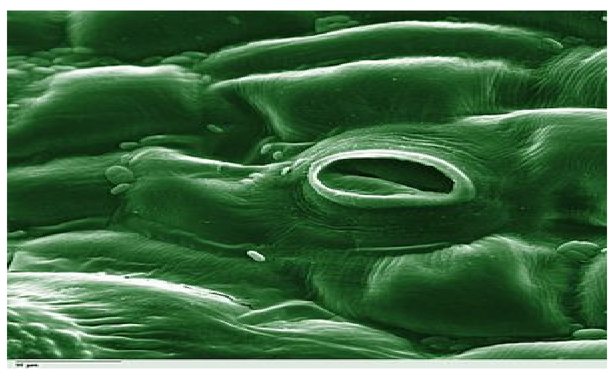
palisade layer
-cells are tall,
-closely packed to absorb maximum light.
-many chloroplasts.
-most photosynthesis takes place in the palisade cells.
-**photosynthesis,**
- **food**
-$\mathbf{O_2}$

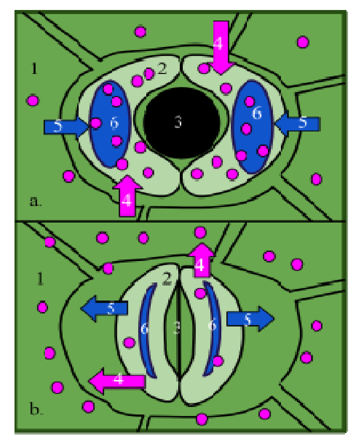
spongy layer
vascular bundles:
- xylem & phloem





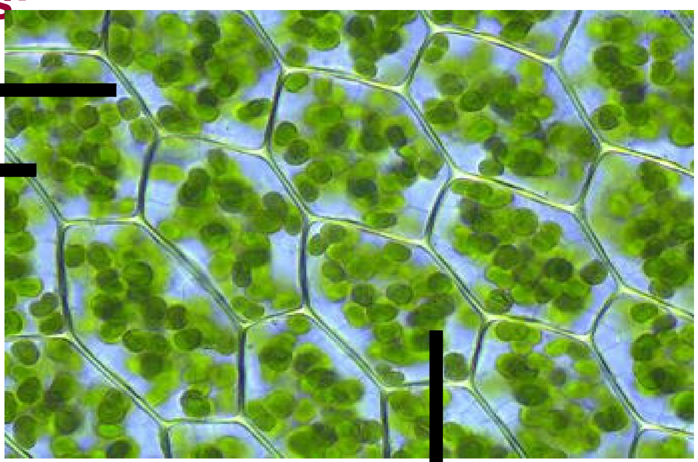
Lower Epidermis
Stomata





Biochemical leaf composition

A typical cell of green fresh leaf contains:



-Water (vacuole) 90-95%

-dry matter : 5-10 %

• Cellulose 15-10 %

•Hemicellulose 10-30%

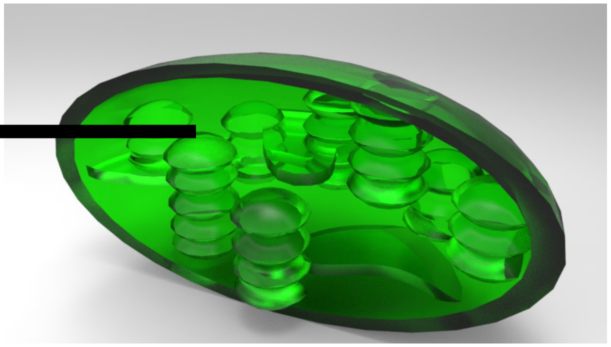
•Proteins 10-20%]

•Lignin 5-15%

•Starch 0.2-2.7%

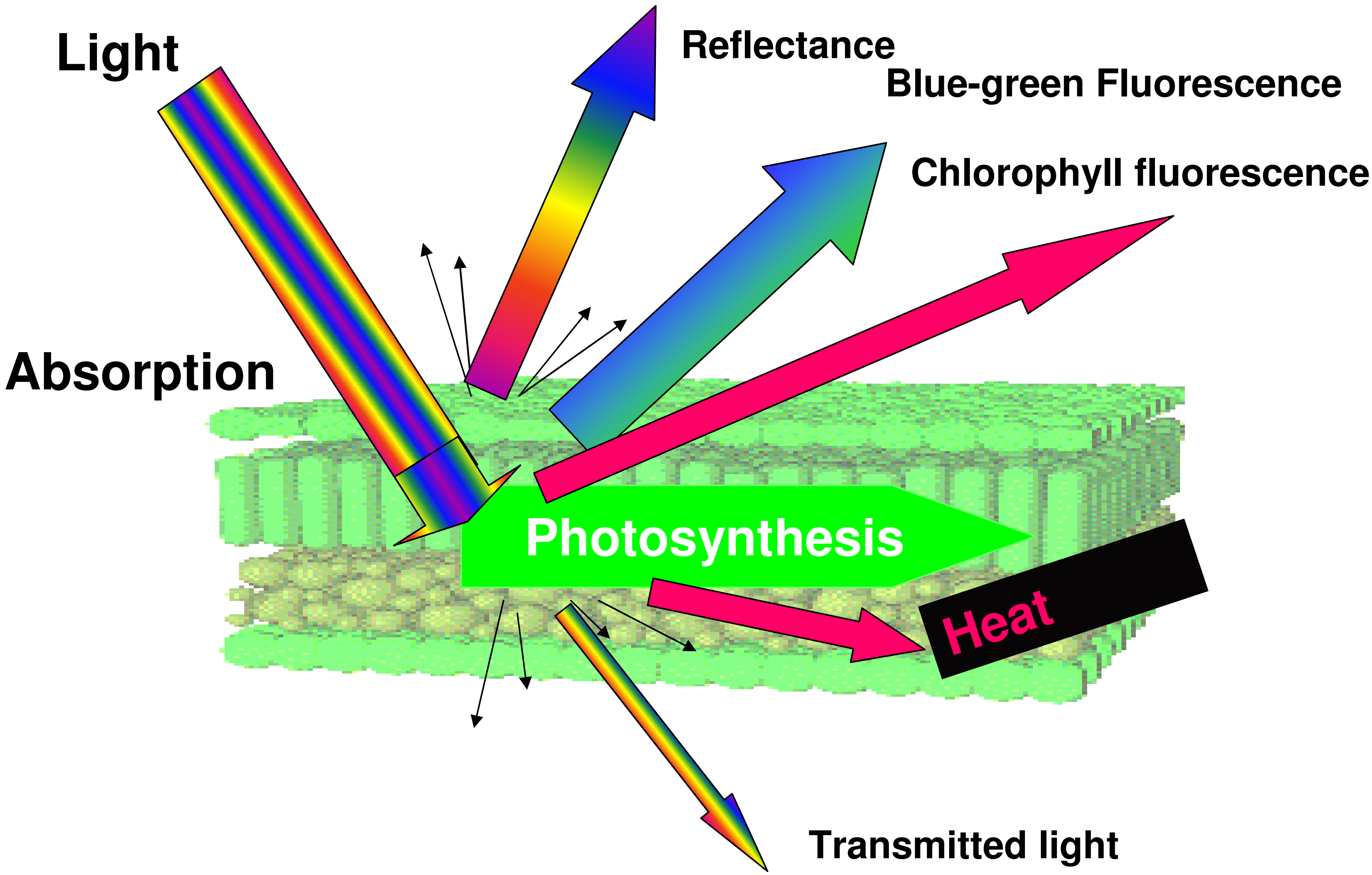
•Sugar

•Chloroplasts (Chlorophyll *a, b*)



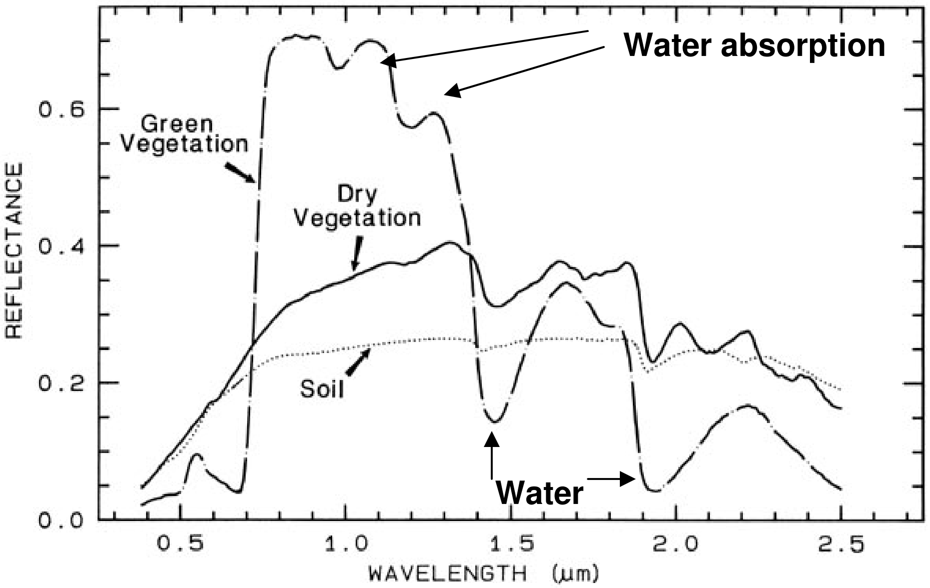
•Other pigments (Carotenoids, anthocynin, brown pigments,Flavons, etc.)

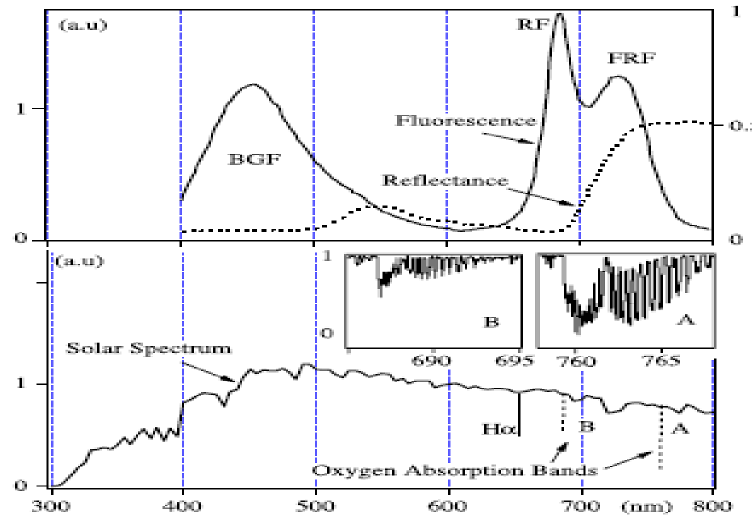
Schematic diagram representing interaction of plant's leaf with light

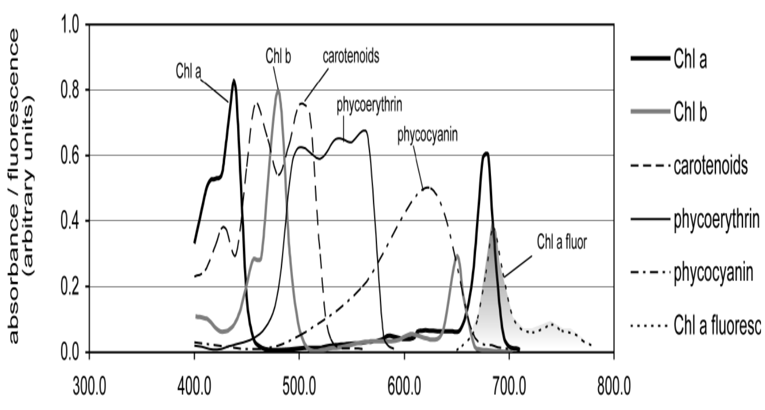


Energy conservation: R(l) + T(l) + A(l) = 1

Reflectance and fluorescence signals





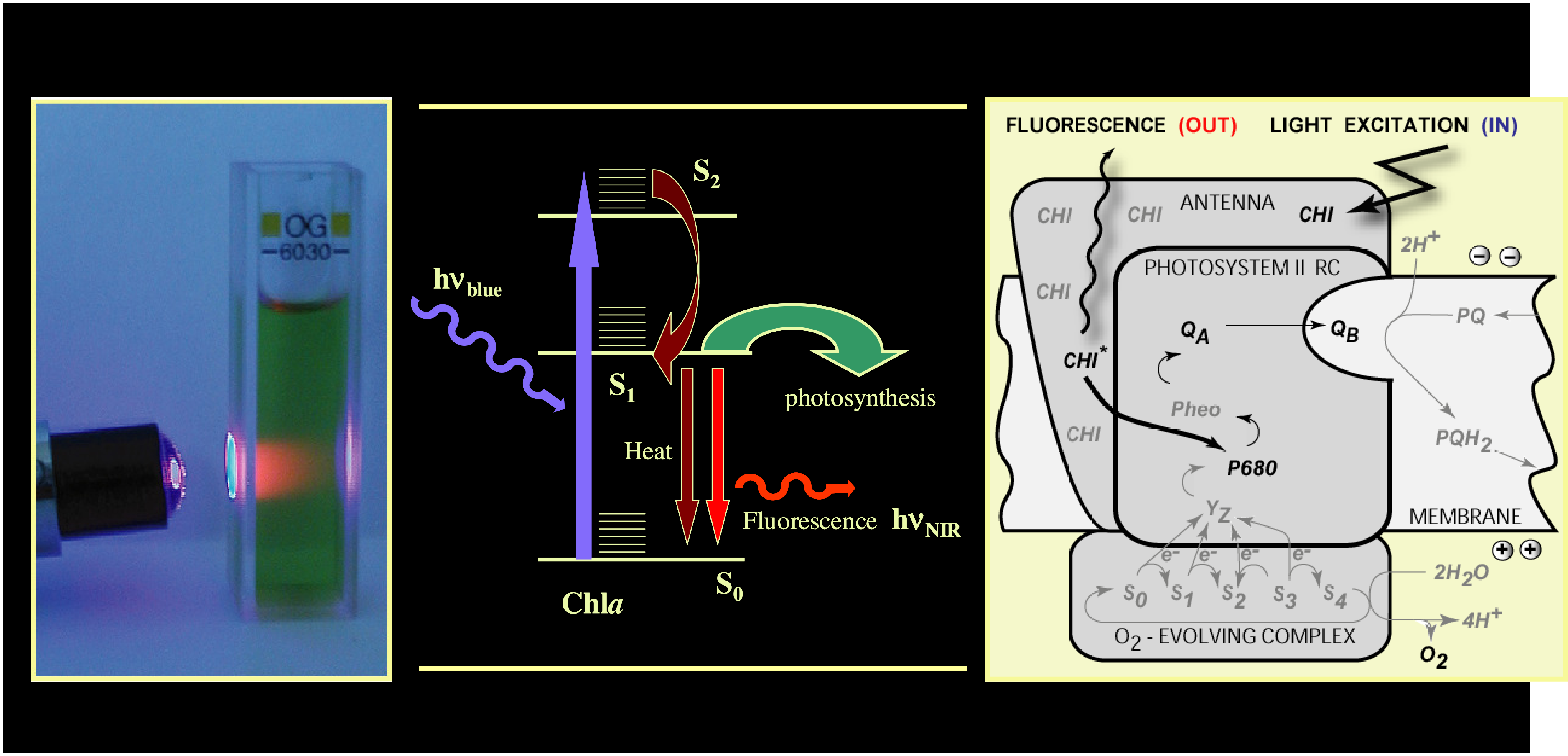


Govindjee (2004)

Reflectance is being measured at various level and many vegetation indexes has been derived.

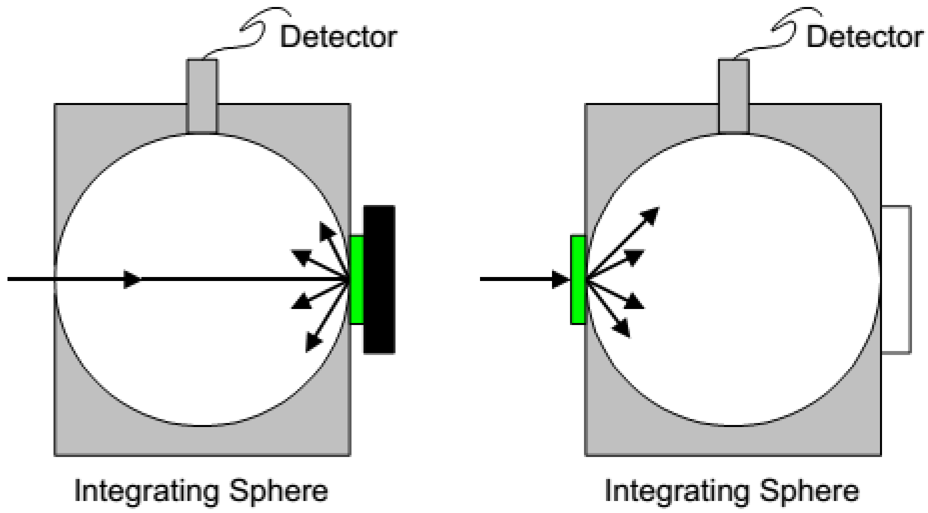
Steady state Fluorescence at Fraunhofer lines will be measured in proposed FLEX mission

Chlorophyll fluorescence competes with photosynthesis for excitation energy



ChlF can be used as a non –invasive reporter to study photosynthetic yield

Integrating sphere for accurately measurements of reflectance



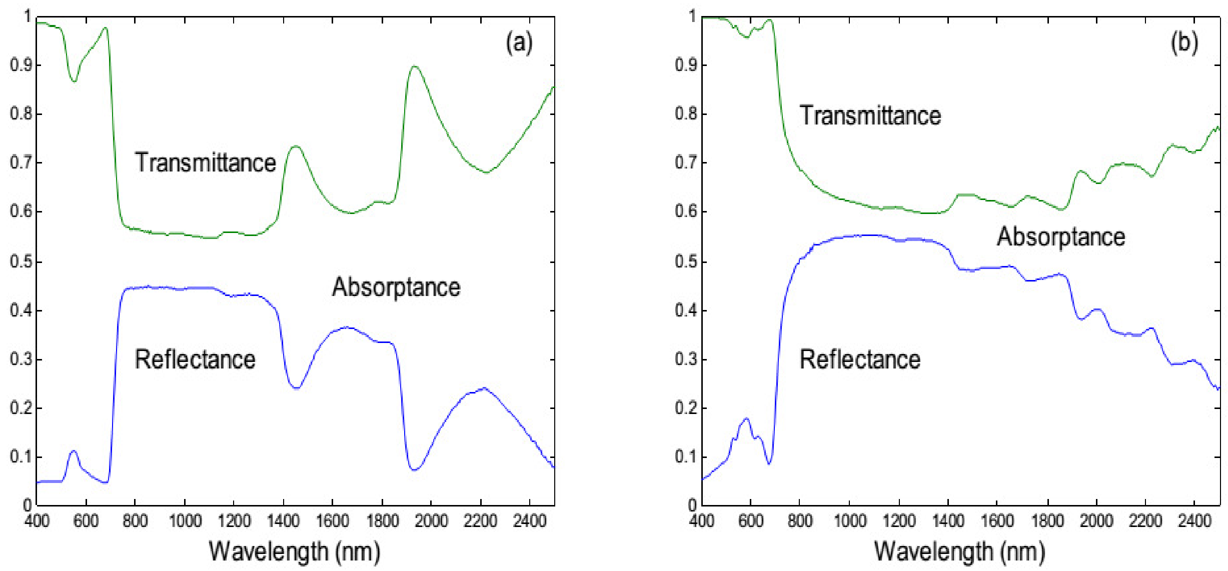
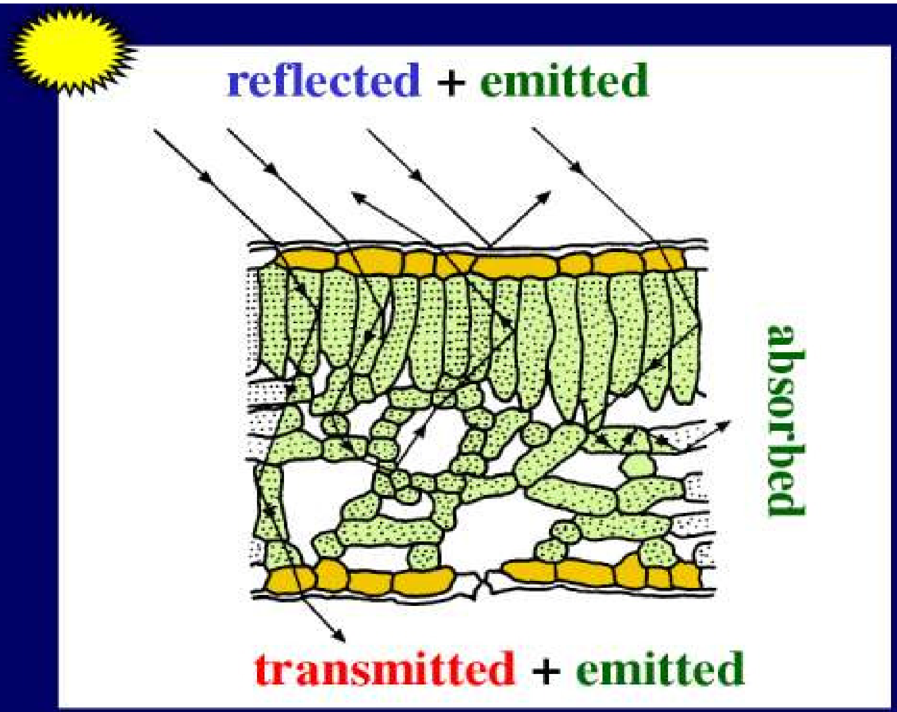


Fig. 2: Reflectance and transmittance spectra of (a) fresh and (b) dry poplar leaves

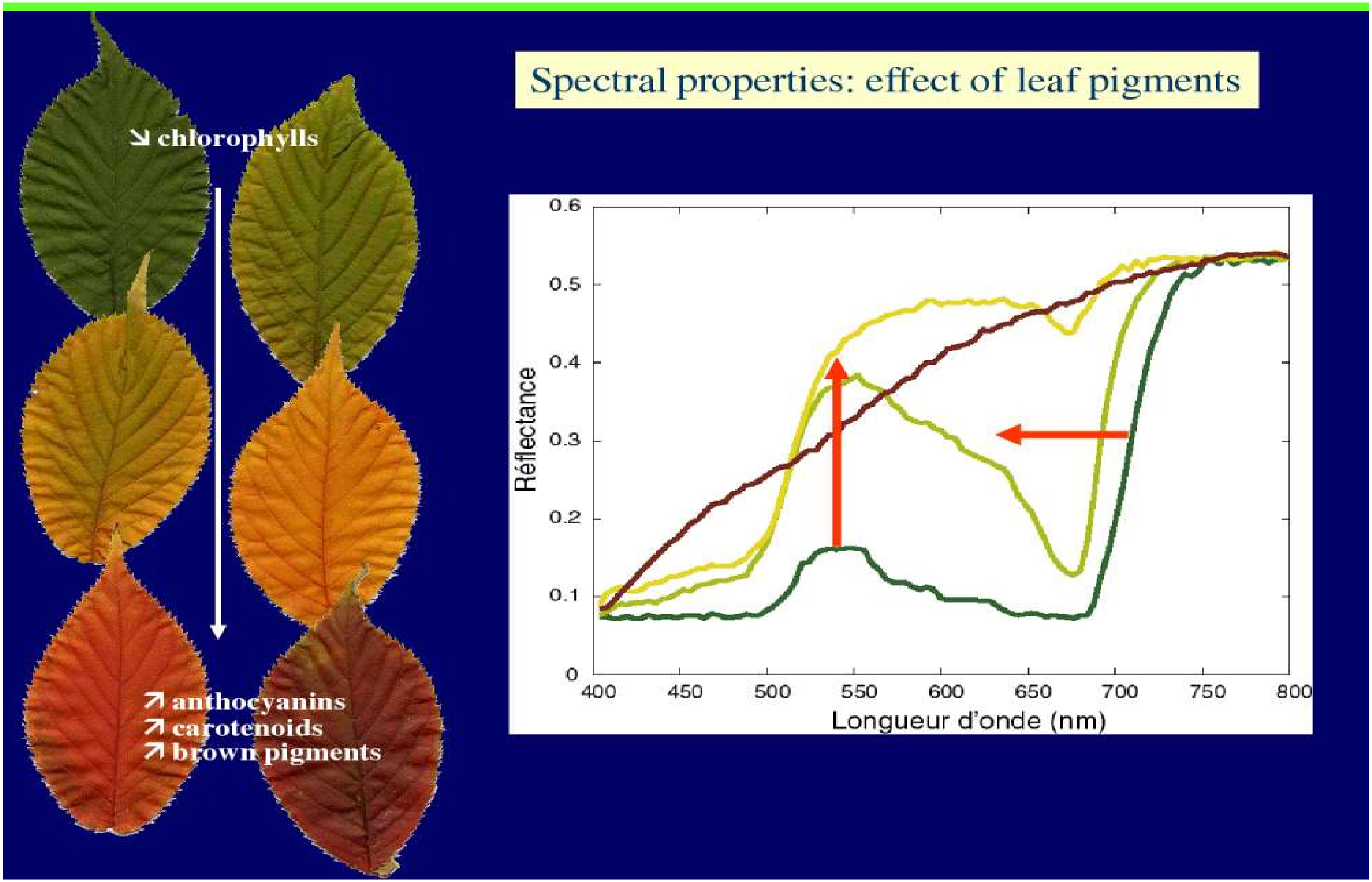
Propagation of photons in leaf

Tessa Traeger, 1997, Sight

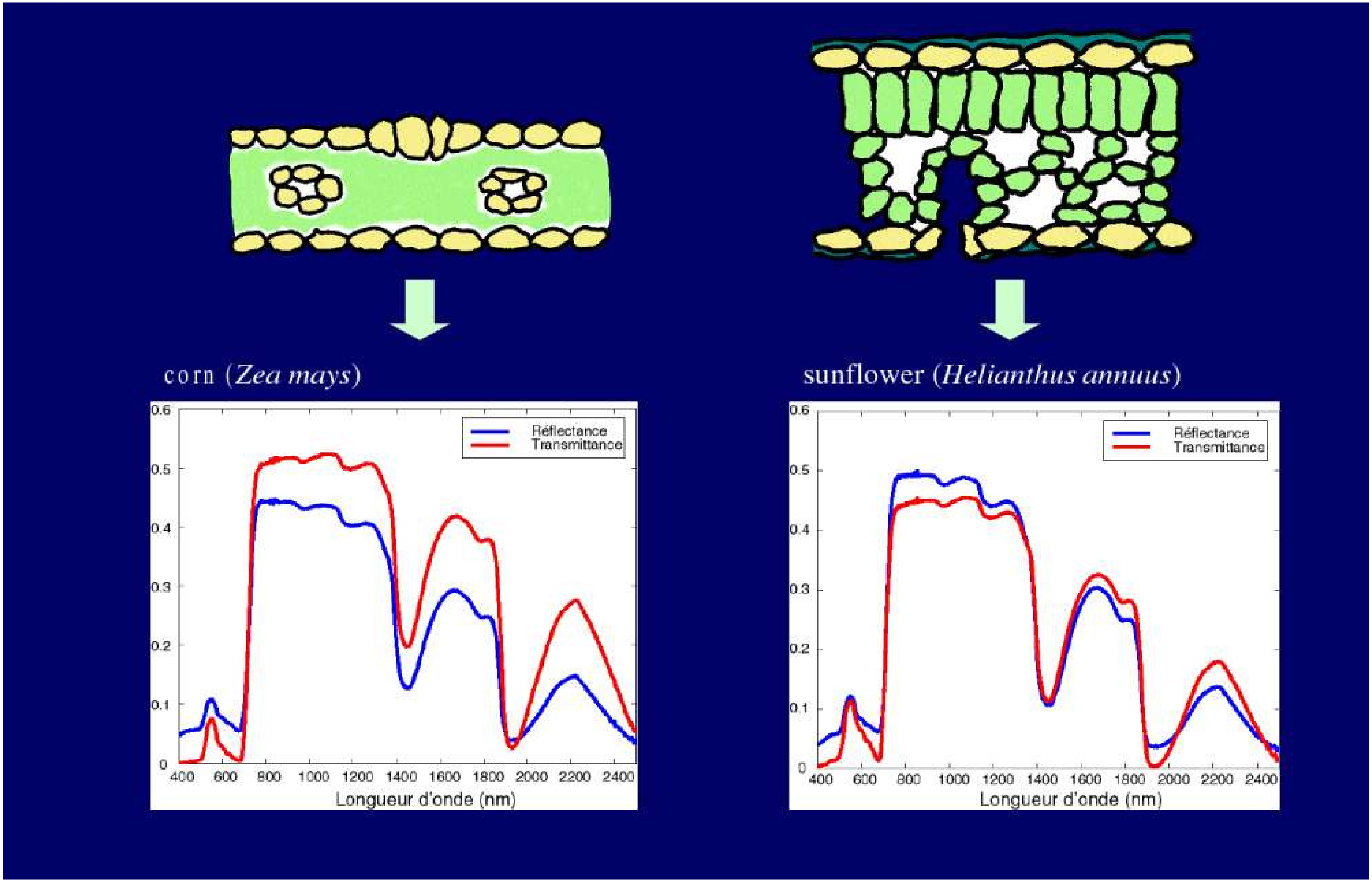


T.R. Sinclair, M.M. Schreiber & R.M. Hoffer, 1973, Diffuse reflectance hypothesis for the pathway of Solar radiation through leaves, *Agronomy Journal*, 65:276-283

Spectral properties: effect of leaf pigments



Spectral properties: effect of leaf internal structure

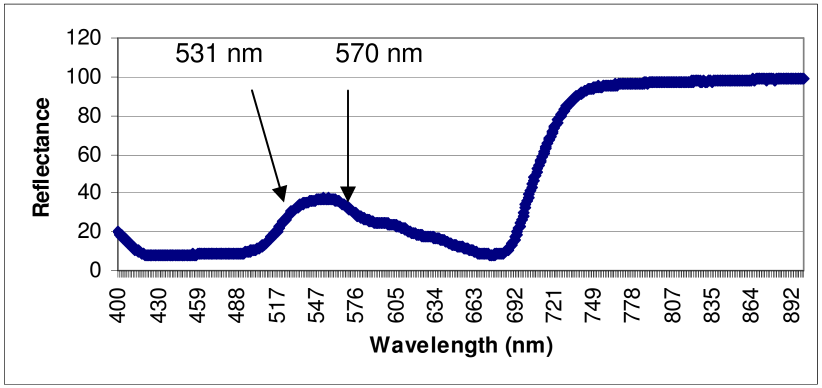


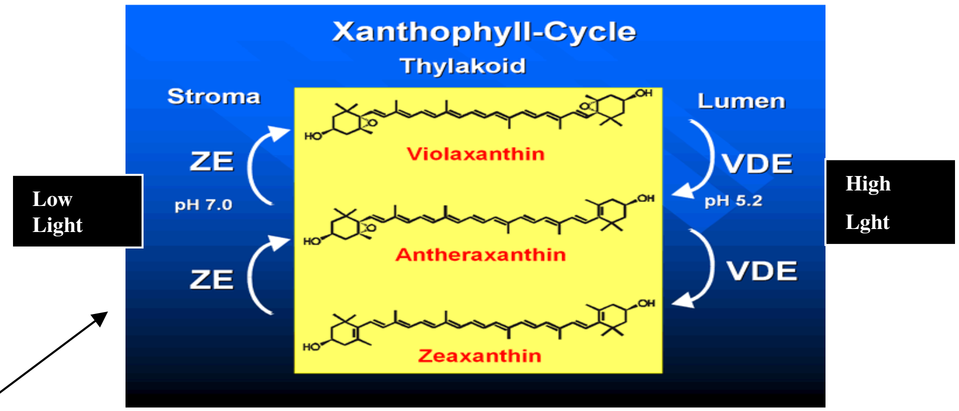
VEGETATION INDEX: Two wavelength dependent Indexes

Normalized Difference Vegetation Index (NDVI)	$NDVI = (R_{NIR} - R_{red})/(R_{NIR} + R_{red})$	Rouse *et al.* (1974)
Renormalized Difference Vegetation Index (RDVI)	$RDVI = (R_{800} - R_{670}) / \sqrt{(R_{800} + R_{670})}$	Rougean and Breon, (1995)
Simple Ratio Index (SR)	SR = RNIR/Rred	Jordan (1969); Rouse et al. (1974)
Modified Chlorophyll Absorption in Reflectance Index (MCARI1)	$MCARI1 = 1.2 * [2.5 * (R_{800} - R_{670}) - 1.3 * (R_{800} - R_{550})]$	Haboudane et al. (2004)
Modified Chlorophyll Absorption in Reflectance Index (MCARI2)	$MCARI2 = \frac{1.5 * [2.5 * (R_{800} - R_{670}) - 1.3 * (R_{800} - R_{550})]}{\sqrt{(2 * R_{800} + 1)^2 - (6 * R_{800} - 5 * \sqrt{R_{670}}) - 0.5}}$	Haboudane et al. (2004)
Improved SAVI with Self-Adjustment Factor L (MSAVI)	$MSAVI = \frac{1}{2}\left[2 * R_{800} + 1 - \sqrt{(2 * R_{800} + 1)^2 - 8 * (R_{800} - R_{670})}\right]$	Qi et al. (1994)
Optimized Soil-Adjusted Vegetation Index (OSAVI)	OSAVI = (1 + 0.16) * (R800 – R670) / (R800 + R670 + 0.16)	Rondeaux et al. (1996)
Greenness Index (G)	$G = (R_{554})/(R_{677})$	-
Modified Chlorophyll Absorption in Reflectance Index (MCARI)	$MCARI = [(R_{700} - R_{670}) - 0.2 * (R_{700} - R_{550})] * (R_{700} / R_{670})$	Daughtry *et al.* (2000)
Transformed CARI (TCARI)	$TCARI = 3 * [(R_{700} - R_{670}) - 0.2 * (R_{700} - R_{550}) * (R_{700} / R_{670})]$	Haboudane *et al* (2002)
Triangular Vegetation Index (TVI)	$TVI = 0.5 * [120 * (R_{750} - R_{550}) - 200 * (R_{670} - R_{550})]$	Broge and Leblanc (2000)
Zarco-Tejada & Miller	$ZM = (R_{750})/(R_{710})$	Zarco-Tejada *et al.* (2001)
Simple R. Pigment Ind. (SRPI)	$SRPI = (R_{430})/(R_{680})$	Peñuelas et al. (1995)
Normalized Phaeophytinization Index (NPQI)	$NPQI = (R_{415} - R_{435})/ (R_{415} + R_{435})$	Barnes et al. (1992)
Photochemical Reflectance Index (PRI)	$PRI = (R_{531} - R_{570})/(R_{531} + R_{570})$	Gamon et al. (1992)
Normalized Pigment Chlorophyll Index (NPCI)	$NPCI = (R_{680} - R_{430})/ (R_{680} + R_{430})$	Peñuelas et al. (1994)
Carter Indices	$Ctr1 = (R_{695})/(R_{420})$ $Ctr2 = (R_{695})/(R_{760})$	Carter (1994) Carter et al. (1996)
Lichtenthaler Indices	$Lic1 = (R_{800} - R_{680})/ (R_{800} + R_{680})$ $Lic2 = (R_{440})/(R_{690})$	Lichtenthaler et al. (1996)
Structure Intensive Pigment Index (SIPI)	$SIPI = (R_{800} - R_{450})/ (R_{800} + R_{650})$	Peñuelas et al. (1995)
Gitelson and Merzlyak	$GM1=R_{750}/R_{550}$ $GM2=R_{750}/R_{700}$	Gitelson & Merzlyak (1997)

Photochemical reflectance index (PRI)
Normalized Differential Vegetation Index (NDVI)

Change in De-epoxidation state of Xanthophylls cycle could be detected by measuring PRI





$$\mathbf{PRI = (R_{531}-R_{570)}/(R_{531}+R_{570})}$$

R_{531} is sensitive to change in Xanth's Cycle Epoxidation state

R_{570} is a reference, unaffected by Xanth's Cycle Epoxidation state.

Quite high variability in day, hours, minutes and even second.

Seasonal variability is also seen

$$\mathbf{NDVI = (R_{far\text{-}red}-R_{red})/(R_{far\text{-}red}+R_{red})}$$

- PRI - a way of dissipating excess light to protect the photosynthetic apparatus (Gamon et al. 1990).
- conversion of violaxanthin to zeaxanthin through xanthophyll cycle.

VEGETATION INDEX: Three wavelength dependent Indexes

$$R^{-1} \propto R_{\infty} = a / b_b$$

Gitelson et al (2006)

a = Sum of the Absorption coefficients for the pigments of interest a_p and other pigments a_0

b_b = Backscattering coefficient

$$[R(\lambda_1)^{-1} - R(\lambda_2)^{-1}] \times R(\lambda_3) \propto a_p$$

$R(\lambda)_1$ = Reflectance maximally sensitive to the absorption of particular pigments a_p

$R(\lambda)_2$ = Reflectance where the absorption is much lower than $R(\lambda)_1$

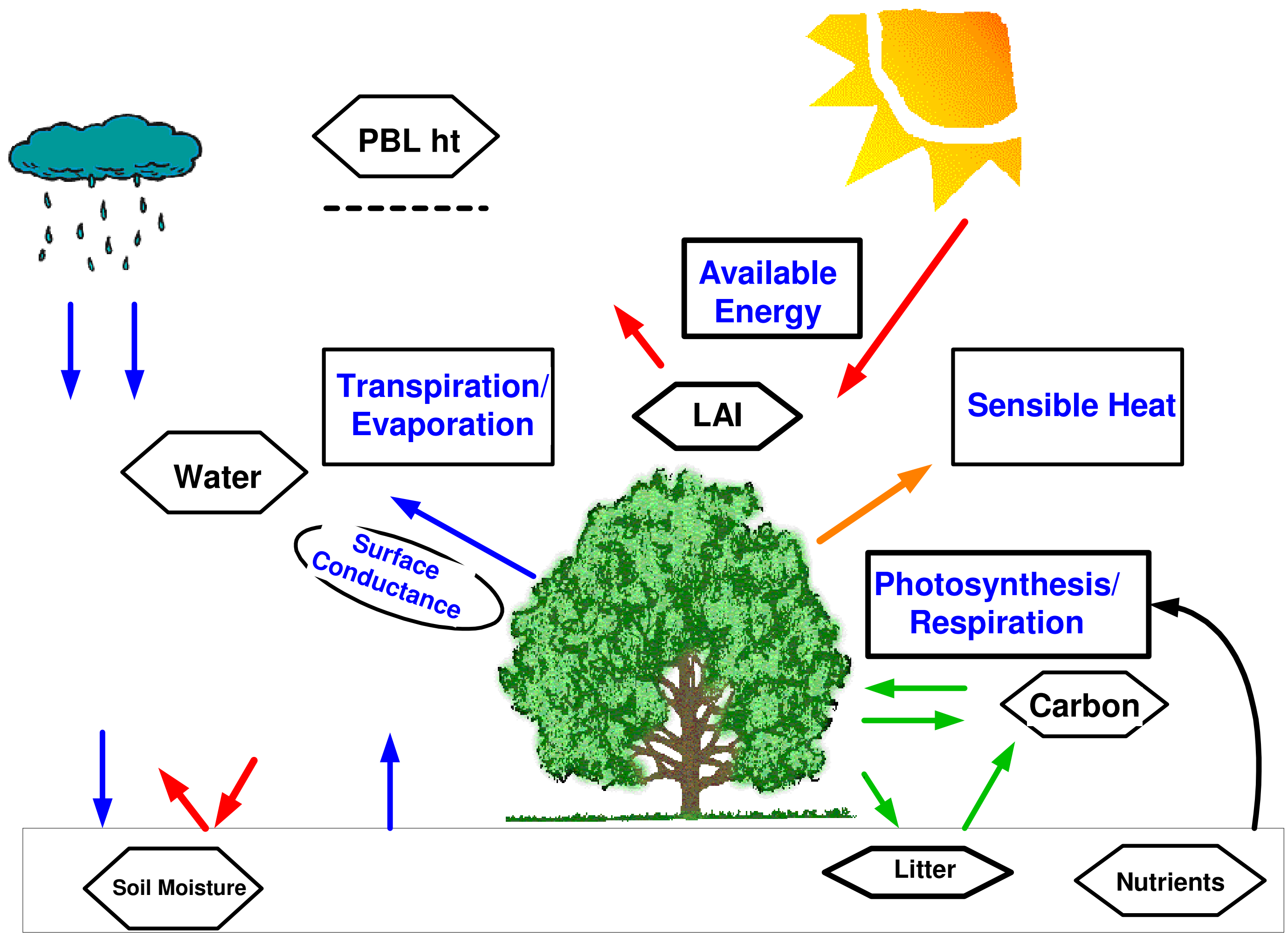
$R(\lambda)_3$ = Reflectance where backscattering controls the reflectance

Table: Spectral bands for retrieving pigment content from leaf reflectance

Pigment	λ_1	λ_2	λ_3
Chlorophylls, Anth-free	540 – 560	760 – 800	760 – 800
Chlorophylls, Anth-free	690 – 720	760 – 800	760 – 800
Chlorophylls, Anth-cont	690 – 720		760 – 800
Carotenoids	510 – 520	540 – 560	760 – 800
Carotenoids	510 – 520	690 – 710	760 – 800
Anthocyanins	540 – 560	690 – 710	760 – 800

Three wavelength dependent indices proved to be very useful for tracking of particular pigments.

System Complexity:
Interconnection of Key Ecosystem Processes



Remote sensing of vegetation products scaling of biophysical processes : A challenge

Leaf area index (LAI) = Leaf area per unit ground surface area

= *leaf area / ground area, m2 / m2*)

~ projected leaf area m2

Fraction of absorbed photosynthetic active radiation (fPAR)

= *radiation absorbed by vegetation for photosynthesis*

/ total incoming PAR between 400–720 nm

- Primary productivity of photosynthesis
- evapotranspiration
- reference tool for crop growth

How to measure LAI?

Direct Methods

-Area harvest (grasslands, agriculture)

-application of allometric equations to stand diameter data,

-leaf litterfall

collect leaves during ***leaf fall in traps*** *and compare to area measurements. Leaf are is measured using a scanner and image processing software collect leaves from the canopy and conduct measurements. Is* ***destructive****, especially with evergreens due to the difficulties and destructiveness of direct methods for determining LAI, they are mostly used as a reference for indirect methods that are easier and faster to apply. disadvantages include:*

Destructive; time consuming; expensive, especially if the study are is large

Indirect Methods

indirect contact LAI measurements (very subjective and labor intensive)

plumb lines inclined point quadrates

indirect non-contact measurements (typically preferred)

hemispherical photography: estimate LAI from analyzing upward looking fisheye photographs taken beneath the plant canopy

How to measure LAI?

Beer's Law predicts light transmission through a turbid medium, in terms of the relative light transmission (I/Io), as an exponential function of leaf area index (L) and a proportionality constant (k); k reflects the geometric influence associated with the angle between leaves and the sun:

$$I/I_0=\exp(-kL)$$

Remote sensing of vegetation products scaling of biophysical processes : A challenge

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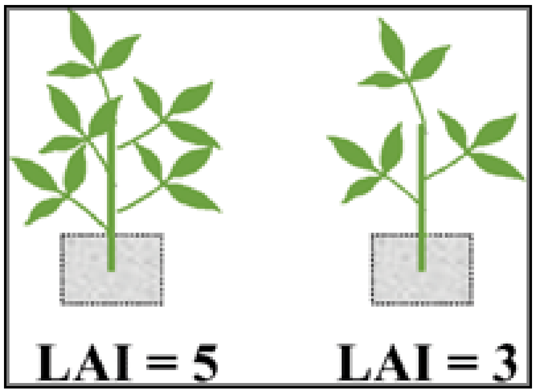
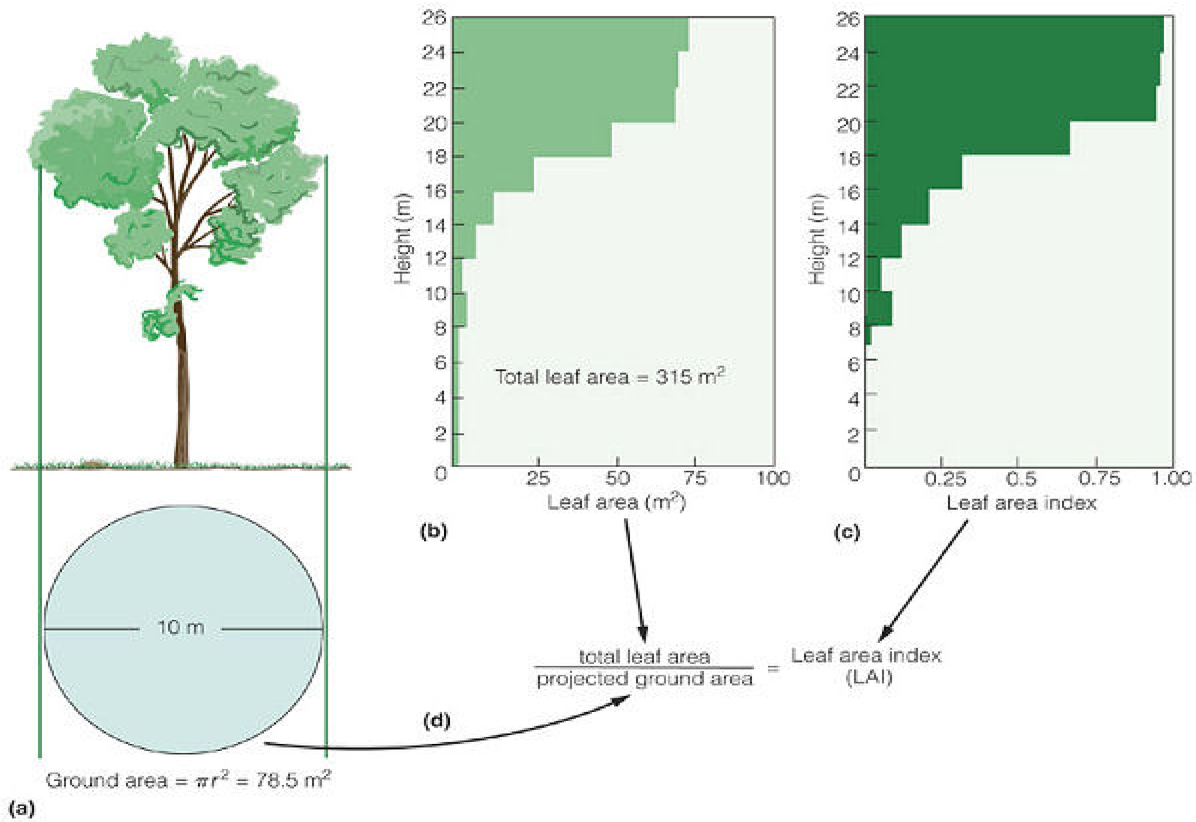
= *leaf area / ground area, m2 / m2*)





LAI ranges from zero (bare ground) to over 10 (dense conifer forests

Remote sensing of vegetation products scaling of biophysical processes : A challenge

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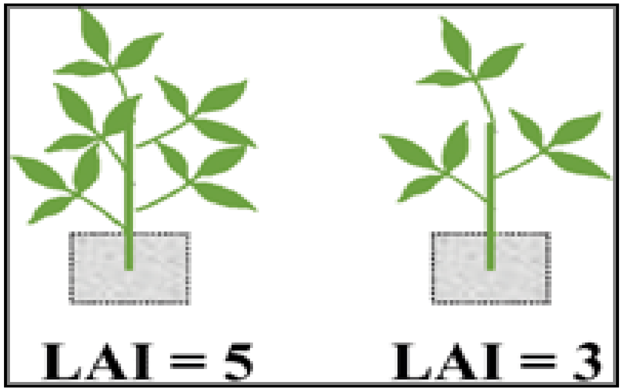

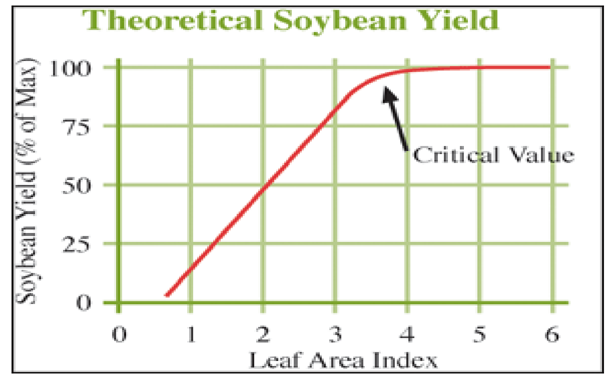

LAI

How to measure LAI?

pines trees
LAI = 2 - 4)

temperate deciduous forest
LAI = 3 - 5

tropical rain forest
LAI= 6-10

Productivity Estimation

- NDVI has been applied in innumerable studies for estimation of vegetation biomass, greenness, primary production, dominant species, leaf are index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR)

$$fAPAR = a*NDVI_{toc} + b$$

$$APAR = fAPAR*PAR$$

GPP can be calculated from remotely sensed NDVI

$$GPP = \varepsilon \sum n(a*NDVI + b)PAR$$

$$\mathbf{NPP = GPP - R_{(autotropic)}}$$

Net ecosystem exchange of CO_2 (g C m^{-2} $time^{-1}$) $\mathbf{NEE = GPP - R_{total}}$

R_{total} is the sum of all autotrophic and hetrotrophic respiration over some time period (Hunt et al. 2002)

Direct and indirect methods for estimation of LAI, fAPAR, and modeling NPP of different types of terrestrial ecosystem

Gower et al. (1999)

The TERRA, EOS-AM platform was launched on December 19, 1999 and started to provide global primary production (namely, MOD17) on the 8-day interval with nominal 1-km resolution beginning on Feb 24, 2000 (Zhao et al. 2005).

Turner et al. (2006) tested the performance of NPP and GPP on nine sites varying widely in biome types and land use, and concluded an over estimation at low productivity sites and underestimation at higher productivity site of these parameters while comparing satellite and eddy co-variance technique.