ENGO 697

Remote Sensing Systems and Advanced Analytics

Session 5: How to develop radiative transfer models in hypers/multi-spectral systems

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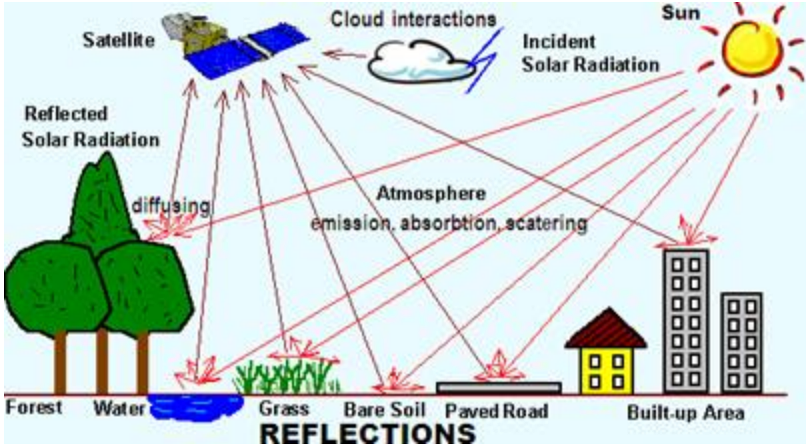
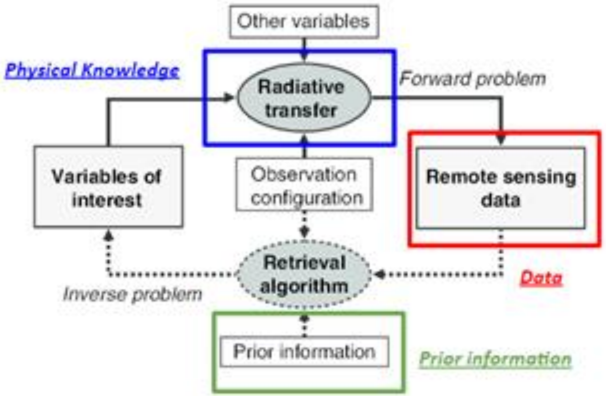
Outline

- ➔ Radiative transfer equations
- ➔ Hyperspectral RTMs: Prospect, Sail and Prosail
- ➔ Simulation and sensitivity analysis
- ➔ Questions

Theoretical Framework for Environmental Remote Sensing





Pictures from maps.unomaha.edu, Baret and Buis (2008)

Forward model / radiative transfer model (RTM):

Y = f(X)

(1) Y: *remote sensing images* captured by the sensor

(2) X: *environmental variable* that you want to estimate, e.g., *crop chlorophyll content, leaf area index, ice concentration, class identity (e.g., diseased class)* etc.

How to characterize f(X)? Examples?

What are the uncertainties and assumptions in f(X)?

Inverse model:

X = g(Y)

What are the approaches to achieve g(.)? Their advantages and disadvantages?

In g(.), how to use all possible information sources, e.g., data, knowledge and prior information?

how to get the “best” g(.) to estimate X?

How to evaluate errors and uncertainties?

Radiative Transfer Model

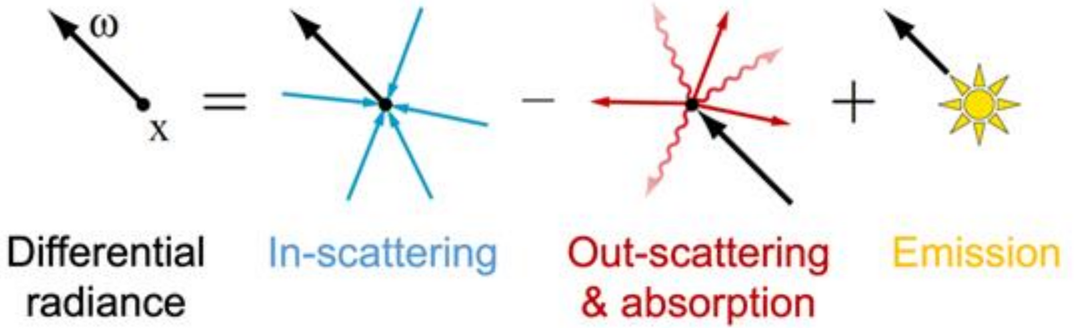
- **Radiation transfer** refers to the physical process of electromagnetic radiation transferring through a medium, which involves absorption, transmission, emission, and scattering processes.

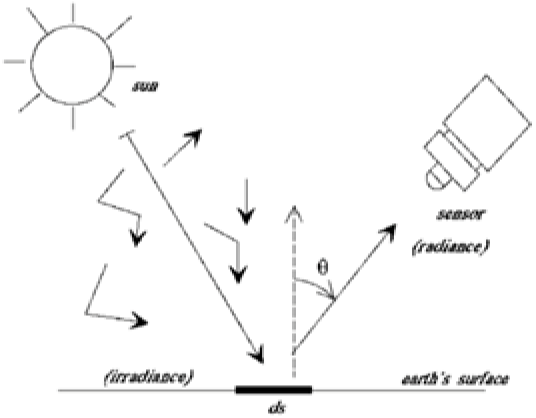
- **Radiative Transfer Models** (RTMs) calculate the energy reflected, absorbed, emitted or transmitted as a function of other influencing factors in a plant canopy or planetary atmosphere.

- RTMs can be used to predict the spectral transmission of the atmosphere, the light reflected or emitted from a plant, and the amount of energy absorbed or emitted at different levels.

Radiative Transfer Equations - how to describe ***<u>the variation of the radiance L per unit distance along ω?</u>***

The equation of radiative transfer simply says that ***<u>as a beam of radiation travels</u>***, it loses energy to absorption, gains energy by emission processes, and redistributes energy by scattering.





$$(\boldsymbol{\omega}\cdot\nabla)L(\boldsymbol{x},\boldsymbol{\omega}) = \sigma_s(\boldsymbol{x})\int_{\mathbb{S}^2} f_p(\boldsymbol{x},\boldsymbol{\omega}_i\to\boldsymbol{\omega})L(\boldsymbol{x},\boldsymbol{\omega}_i)\,\mathrm{d}\boldsymbol{\omega}_i - \sigma_t(\boldsymbol{x})L(\boldsymbol{x},\boldsymbol{\omega}) + Q(\boldsymbol{x},\boldsymbol{\omega})$$

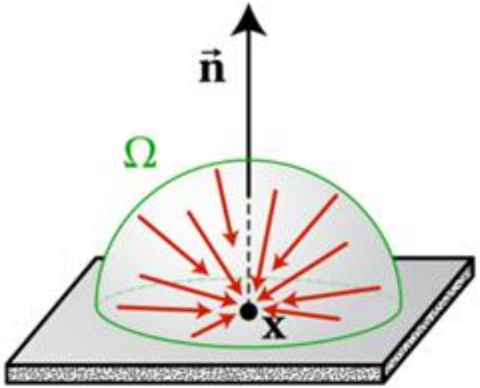
In-scattering | Out-scattering & absorption | Emission

Scattering coefficient: $\sigma_s(\boldsymbol{x}) \in \mathbb{R}_{\geq 0}$,
Phase function: $f_p(\boldsymbol{x},\boldsymbol{\omega}_i\to\boldsymbol{\omega})$, a probability density over $\mathbb{S}^2$ given $\boldsymbol{x}$ and $\boldsymbol{\omega}_i$

The ratio between σ_s and σ_t controls the fraction of radiant energy *not* being absorbed at each scattering and is also known as the *single-scattering albedo*

Source term: $Q(\boldsymbol{x},\boldsymbol{\omega}) \in \mathbb{R}_{\geq 0}$

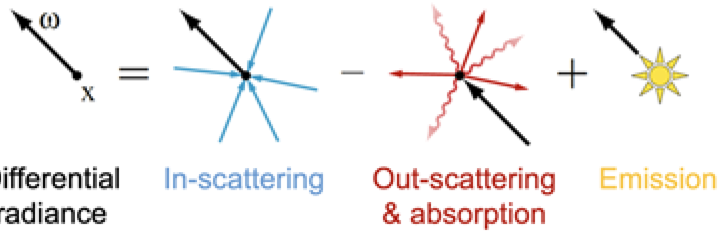
Extinction coefficient: $\sigma_t(\boldsymbol{x}) \in \mathbb{R}_{\geq \sigma_s(\boldsymbol{x})}$
σ_t controls how frequently light scatters and is also known as the *optical density*

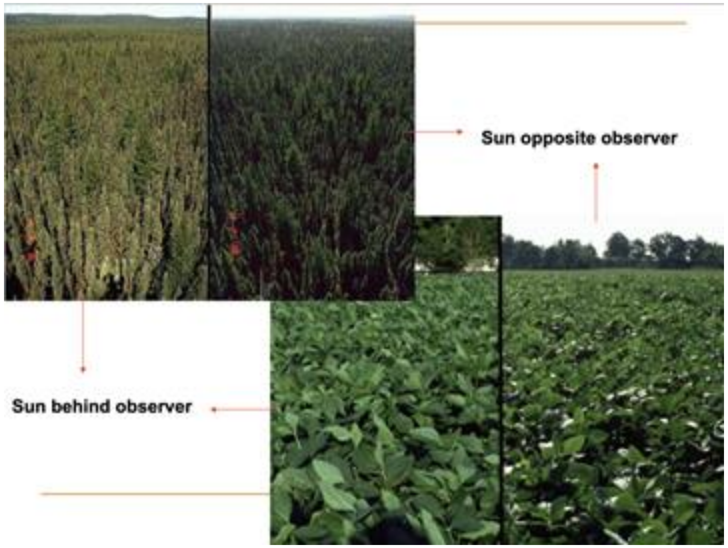


- Differential radiance

$$(\boldsymbol{\omega}\cdot\nabla)L(\boldsymbol{x},\boldsymbol{\omega}) = \left.\frac{\mathrm{d}L(\boldsymbol{x}+\tau\boldsymbol{\omega},\boldsymbol{\omega})}{\mathrm{d}\tau}\right|_{\tau=0} = \lim_{\tau\to 0}\frac{L(\boldsymbol{x}+\tau\boldsymbol{\omega},\boldsymbol{\omega}) - L(\boldsymbol{x},\boldsymbol{\omega})}{\tau}$$

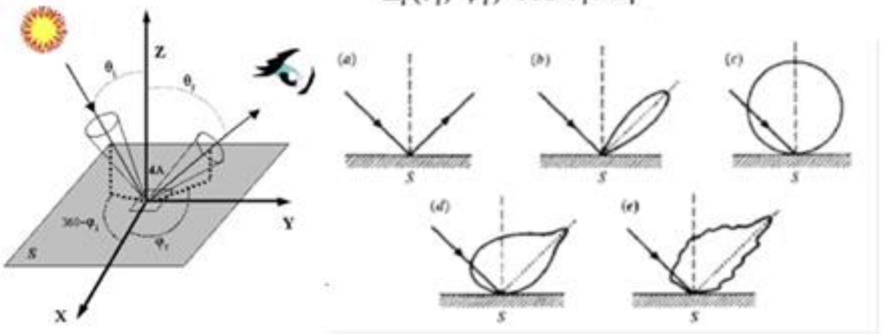
In-scattering - How to describe radiation directional properties? BRDF

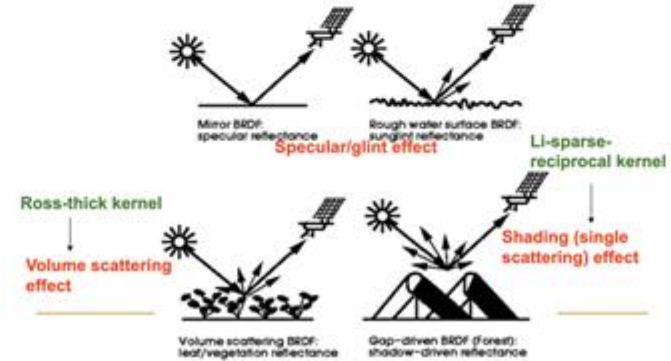




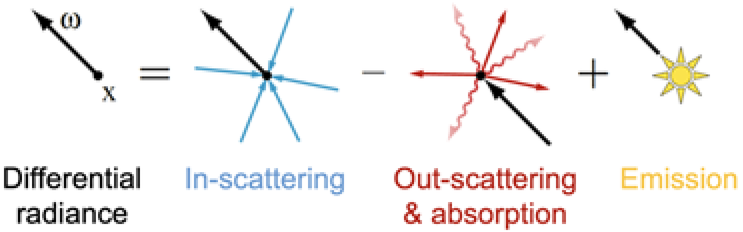
The Bi-directional Reflectance Distribution Function (BRDF) is used to describe the dependence of reflected radiation on the incident (i) and outgoing (v) directions (Nicodemus, 1977).

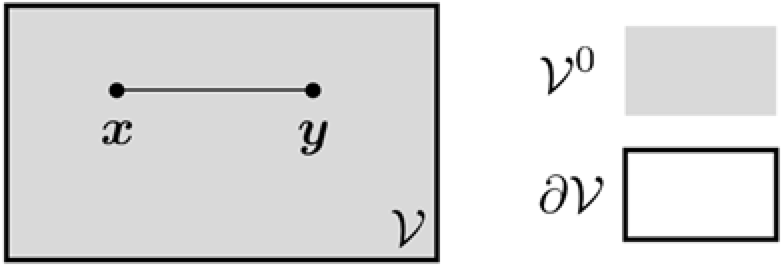
$$B(\theta_i, \phi_i, \theta_v, \phi_v) = \frac{dL_v(\theta_i, \phi_i, \theta_v, \phi_v)}{L_i(\theta_i, \phi_i)\cos\theta_i d\Omega_i}\ \mathrm{sr}^{-1}$$





Out-scattering & absorption - How to quantify ***attenuation***? Beer's Law





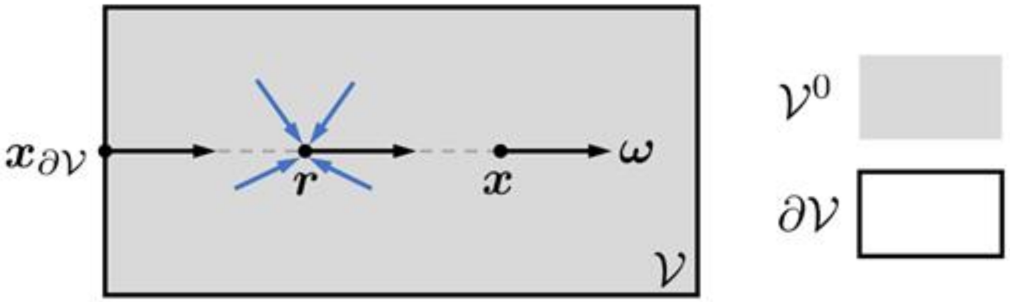
- For any $x, y \in \mathcal{V}$, the attenuation between ***x*** and ***y*** is

$$T(\boldsymbol{x} \leftrightarrow \boldsymbol{y}) := \exp\left(-\int_{(\boldsymbol{x},\boldsymbol{y})} \sigma_t(\boldsymbol{r})\,\mathrm{d}\boldsymbol{r}\right)$$

  - A line integral between ***x*** and ***y***
  - $0 \le T(\boldsymbol{x} \leftrightarrow \boldsymbol{y}) \le 1$ for all ***x*** and ***y***
  - For homogeneous media with $\sigma_t(\boldsymbol{x}) \equiv \sigma_t$,

$$T(\boldsymbol{x} \leftrightarrow \boldsymbol{y}) = \exp(-\|\boldsymbol{x} - \boldsymbol{y}\|\sigma_t)$$

Solving Radiative Transfer Equations - Derive Integral form of RTEs



Attenuation — In-scattering — Emission

$$L(\boldsymbol{x},\boldsymbol{\omega}) = \int_0^{h(\boldsymbol{x},\boldsymbol{\omega})} T(\boldsymbol{r}\leftrightarrow\boldsymbol{x})\left[\sigma_s(\boldsymbol{r})\int_{\mathbb{S}^2} f_p(\boldsymbol{r},\boldsymbol{\omega}_i\to\boldsymbol{\omega})L(\boldsymbol{r},\boldsymbol{\omega}_i)\,\mathrm{d}\boldsymbol{\omega}_i + Q(\boldsymbol{r},\boldsymbol{\omega})\right]\mathrm{d}\tau$$

$$+\, T(\boldsymbol{x}_{\partial\mathcal{V}}\leftrightarrow\boldsymbol{x})\,L(\boldsymbol{x}_{\partial\mathcal{V}},\boldsymbol{\omega}) \quad \text{where } \boldsymbol{r} := \boldsymbol{x} - \tau\boldsymbol{\omega}$$

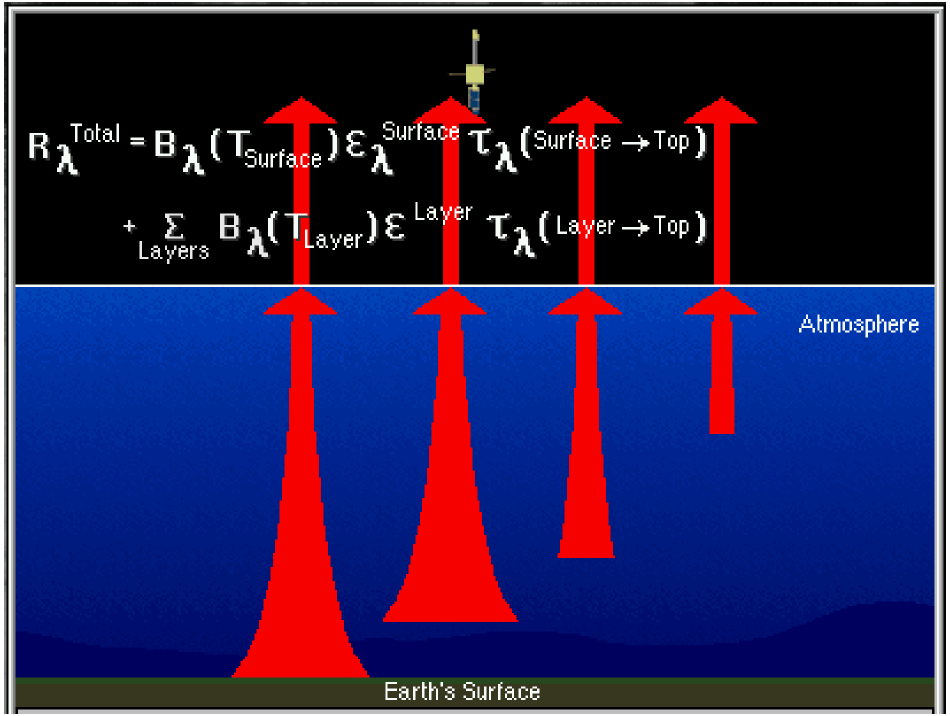
Attenuation — Boundary cond.

(The second term vanishes when $h(\boldsymbol{x},\boldsymbol{\omega}) = +\infty$)

All RTMs follow this general form.

The differences however, are essentially due to the various forms for the emission and absorption coefficients.

Attenuation of Radiative Transfer through the Atmosphere based on Blackbody assumption



The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer is the sum of radiation emissions from the earth-surface and each atmospheric level that are transmitted to the top of the atmosphere.

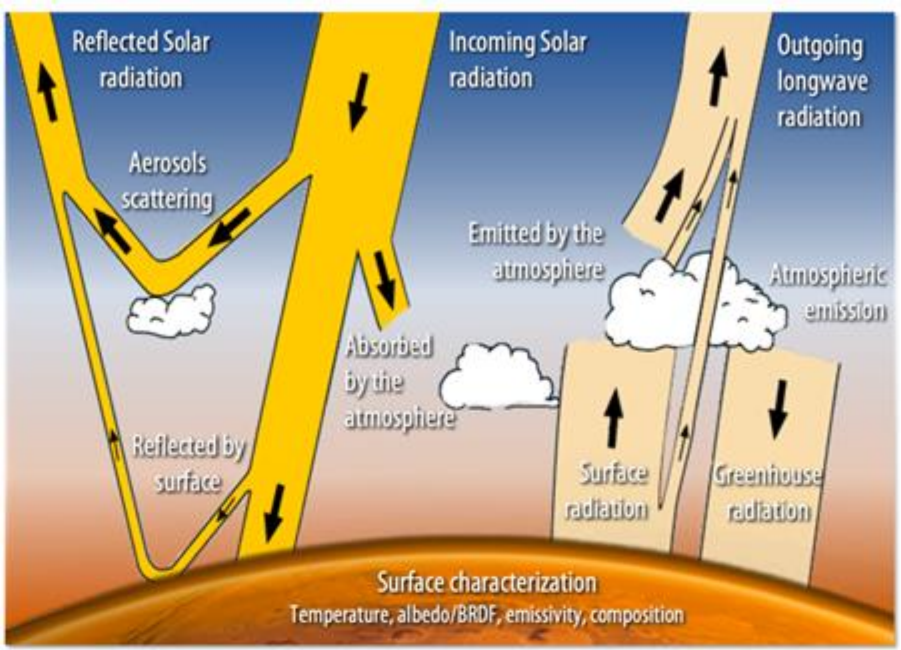
Considering the earth's surface to be a blackbody emitter (emissivity equal to unity), the upwelling radiance intensity, I_λ, for a cloudless atmosphere is given by the expression

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top)$$

$$+ \quad \Sigma\, \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

where the first term is the surface contribution and the second term is the atmospheric contribution to the radiance to space.

Radiative Transfer through the Atmosphere based on Blackbody assumption



The radiance leaving the earth-atmosphere system sensed by a satellite borne radiometer:

$$I_\lambda = \varepsilon_\lambda^{sfc} B_\lambda(T_{sfc})\, \tau_\lambda(sfc - top)$$

$$+ \quad \Sigma\, \varepsilon_\lambda^{layer} B_\lambda(T_{layer})\, \tau_\lambda(layer - top)$$

Q: is the above equation a complete forward model? if not, what else elements are missing?

No, because it only considers:
(1) earth surface emission;
(2) atmosphere emissions;

A complete radiative transfer model needs also to address the following factors:
(1) earth surface reflection;
(2) atmosphere reflection;
(3) changing and complex transmittance due to varying atmospheric conditions, e.g., the heterogeneous effect by cloud
(4) the influence of ground target properties (which are usually the properties we want to estimate), e.g., biophysical, biochemical, geophysical, and geochemical parameters, on earth surface reflection and emission;
(5) the geometry among the radiation source, the sensor and the target.

Input Parameters that Governs Canopy RTMs

There are three main parameters that govern the RTM:

(1) Soil Structure (Soil Brightness, Roughness)

Higher the soil roughness leads to more the anisotropic reflectance

(2) Leaf Biophysical/structural Parameters (LAI, Leaf Angle,etc.)

Higher LAI leads to increased reflectance in Near Infrared (NIR) region

(3) Leaf Biochemical Parameters. (Chlorophyll, Leaf structure)

Higher Chlorophyll content leads to decreased reflectance in Visible Band (400 nm to 725 nm)

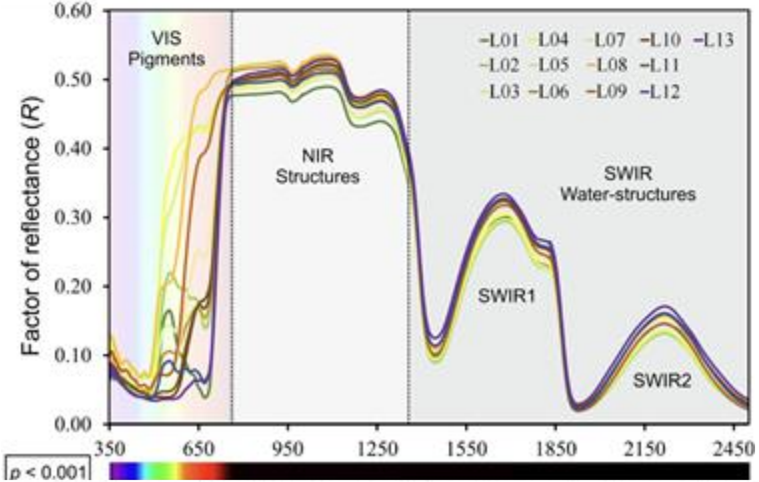
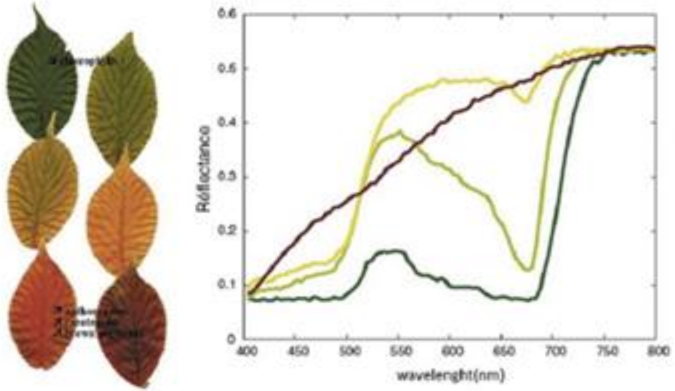
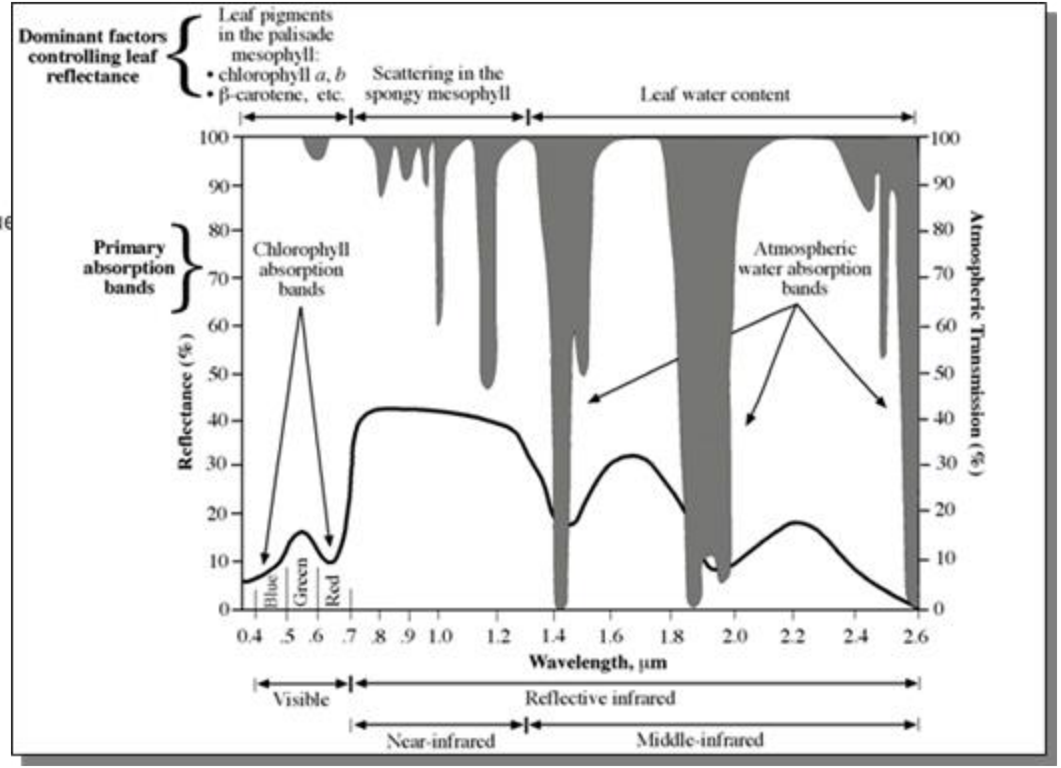


Figure 1. Influence of leaf biochemical changes on reflectance values (Jacque



Reflectance - contributing factors, spectral ranges?

Absorption - contributing factors, spectral ranges?



Different Canopy RTMs

(1) SUIT Model: Developed for a homogeneous canopy;

(1) **PROSPECT Model:** Describe leaf reflectance and transmittance spectrum as a function of some biochemical parameters, e.g., chlorophyll content and water content in leaves;

(1) **SAIL Model:** Describe canopy reflectance spectrum as a function of some biophysical/structural parameters of canopy, e.g., LAI, solar angle;

(1) **PROSAIL Model:** PROSAIL = POSPECT + SAIL, a function of both biochemical and biophysical/structural parameters of leaves and canopy;

(1) GeoSAIL Model: Combination of ***geometric model*** with SAIL model that provides the reflectance and transmittance of the tree crowns and radiative transfer within the crowns is calculated using SAIL.

PROSPECT - Input & Output?

Prospect is a leaf-level RTM that describes the transmittance and reflectance characteristics (400nm to 2500nm) of leaves as a function of some leaf biochemical parameters.

Equivalent Water Thickness (Cw)(cm),

Chlorophyll a + b concentration (Cab)(µg/cm2)

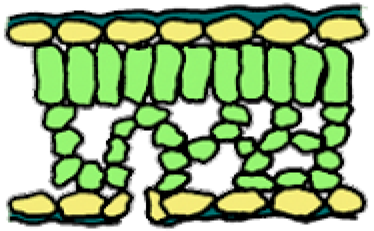
Leaf structure parameter N

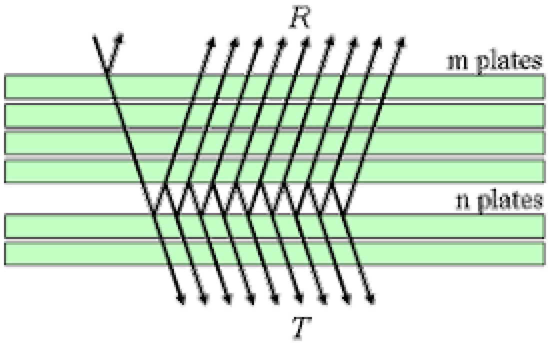
Dry Matter Content (Cm)(g/cm2)

PROSPECT

Directional-Hemispherical Leaf Reflectance and Transmittance Spectrum

Prospect - Model Assumptions & Limitations? (Allen et al. 1969, Jacquemoud and Barret, 1990)



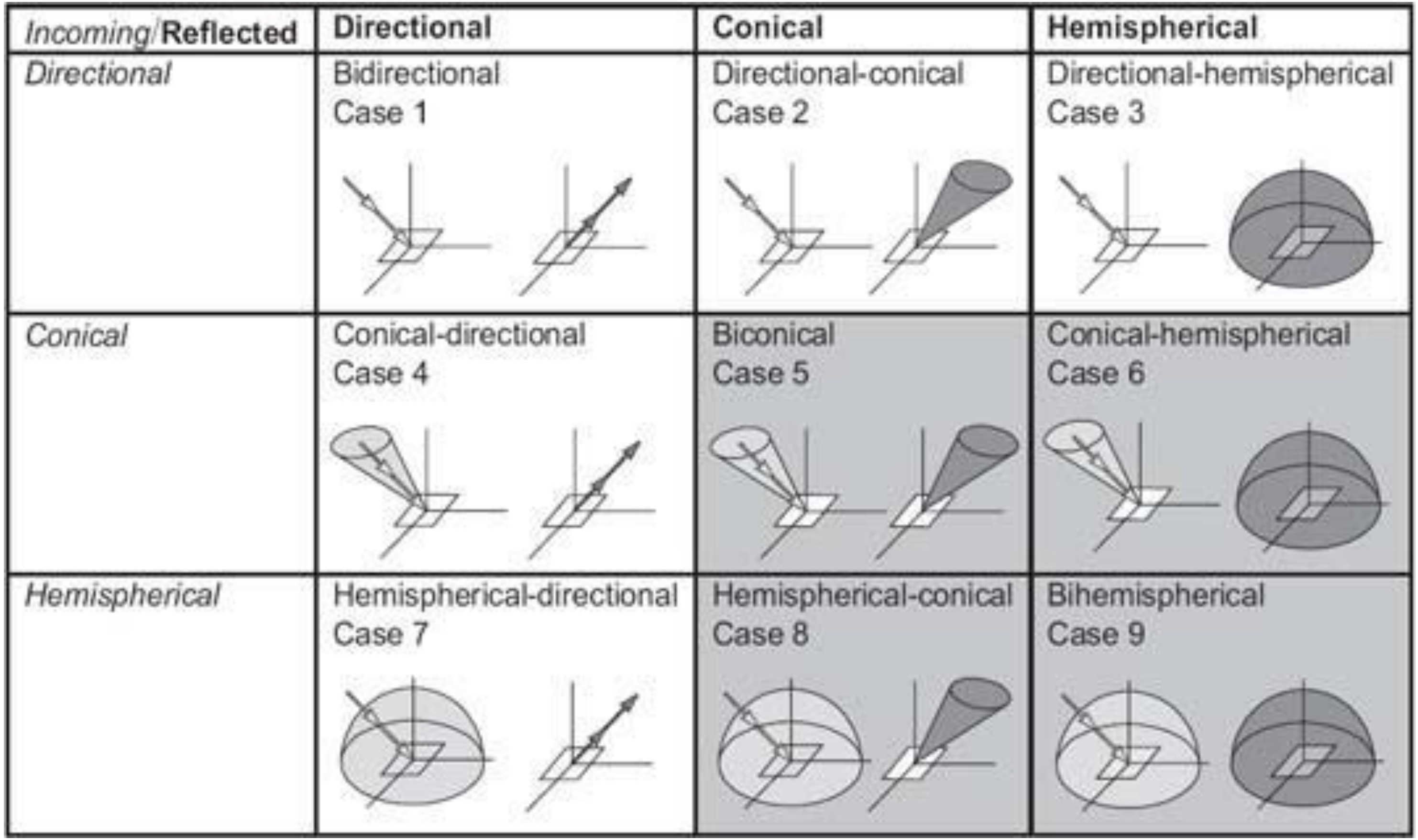


Prospect represents leaf as one or a stack of several absorbing plates with rough surfaces (equivalent to isotropic scattering). http://photobiology.info/Jacq_Ustin.html

Assumptions:

1. Can be decomposed into layers
1. A stack of layers, being parallel to each other
1. Inner-layer homogeneity
1. Rough surface, and isotropic scattering

Differences? Which one for PROSPECT?



Incoming/Reflected	Directional	Conical	Hemispherical
Directional	Bidirectional Case 1	Directional-conical Case 2	Directional-hemispherical Case 3
Conical	Conical-directional Case 4	Biconical Case 5	Conical-hemispherical Case 6
Hemispherical	Hemispherical-directional Case 7	Hemispherical-conical Case 8	Bihemispherical Case 9

From sk.sagepub.com

Prospect Model

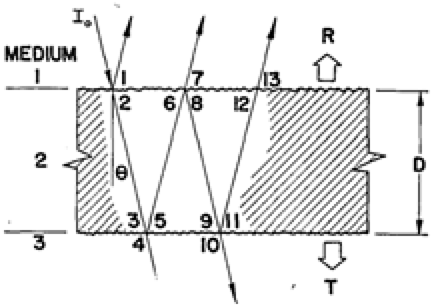


FIG. 1. Multiple reflections produced by a transparent plate with rough surfaces.

TABLE I. Irradiance for regions shown in Fig. 1.

Region	Irradiance
1	R_{12}
2	T_{12}
3	$T_{12}\tau$
4	$T_{12}\tau T_{23}$
5	$T_{12}\tau R_{23}$
6	$T_{12}\tau^2 R_{23}$
7	$T_{12}\tau^2 R_{23} T_{21}$
8	$T_{12}\tau^2 R_{23} R_{21}$
9	$T_{12}\tau^3 R_{23} R_{21}$
10	$T_{12}\tau^3 R_{23} R_{21} T_{23}$
11	$T_{12}\tau^3 R_{23} R_{21} R_{23}$
12	$T_{12}\tau^4 R_{23}^2 R_{21}$
13	$T_{12}\tau^4 R_{23}^2 R_{21} T_{21}$
..	...

$$R + T + A = 1$$

$$R = R_{12} + T_{12}T_{21}\tau^2 R_{23}(1+\tau^2 R_{23}R_{21}+\cdots),$$

$$T = T_{12}\tau T_{23}(1+\tau^2 R_{23}R_{21}+\cdots).$$

$$R = (1-T_{12}) + \frac{\tau^2 T_{12}^2 (n^2 - T_{12})}{n^4 - \tau^2 (n^2 - T_{12})^2},$$

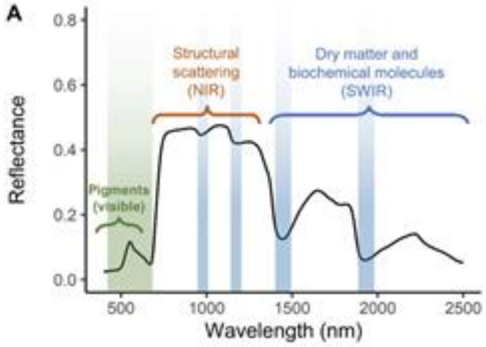
$$T = \frac{\tau n^2 T_{12}^2}{n^4 - \tau^2 (n^2 - T_{12})^2}.$$

Medium index of refraction

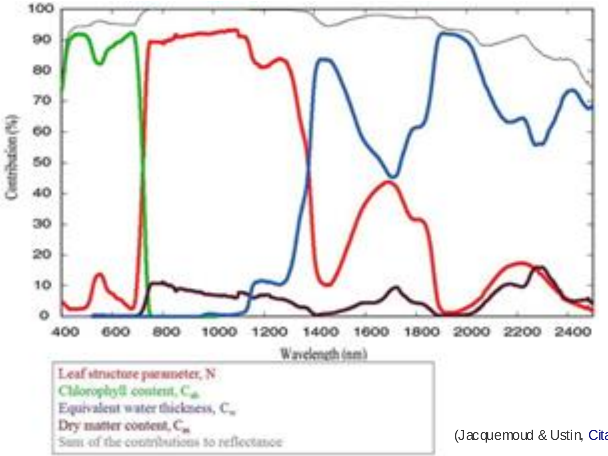
Medium transmittance rate

$$T_{12} = \mu T_1 + (1-\mu) T_2$$

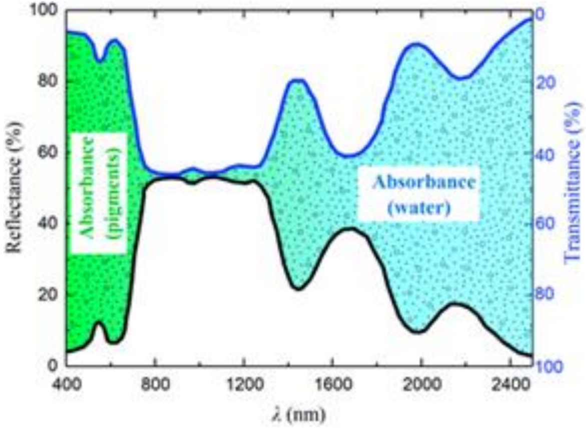
$$T_i = A_i + B_i n + C_i n^2 + D_i n^3$$



Spectral response and sensitivity to biochemical and structural constituents. Green shading represents regions influenced by leaf nitrogen (largely due to chlorophyll a + b), although carotenoids and flavonoids also influence this region, and blue shading indicates wavelengths strongly influenced by water absorption.



(Jacquemoud & Ustin, Citation 2019)



Reflection and transmission spectra of a leaf

From Y. Gao and H. Ye, *Int. J. Heat Mass Transfer*, 2017

Output:

(1) transmittance (400nm to 2500nm) of leaves

(2) Reflectance (400nm to 2500nm) of leaves

Inputs:

(1) Number of structural layers N

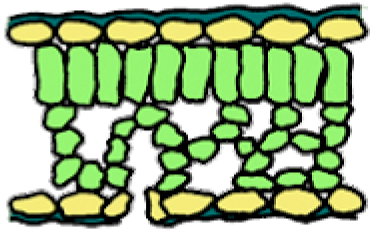
(2) chlorophyll a + b concentration (Cab) (μg/cm2)

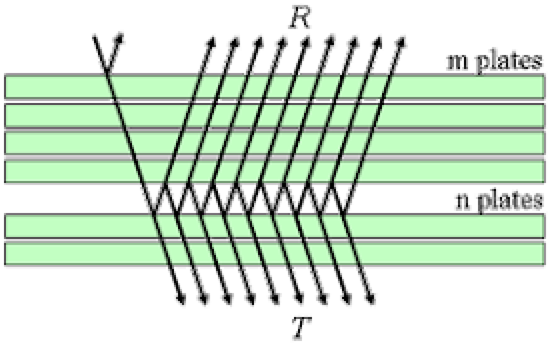
(3) equivalent water thickness (Cw) (cm)

(4) dry matter content (Cm) (g/cm2).

The plate model considers a compact plant leaf as a semi-transparent plate with plane parallel surfaces and initially assumes that the incident light is partially isotropic.

Prospect - Model Assumptions & Limitations? (Allen et al. 1969, Jacquemoud and Barret, 1990)





Prospect represents leaf as one or a stack of several absorbing plates with rough surfaces (equivalent to isotropic scattering). http://photobiology.info/Jacq_Ustin.html

Assumptions:

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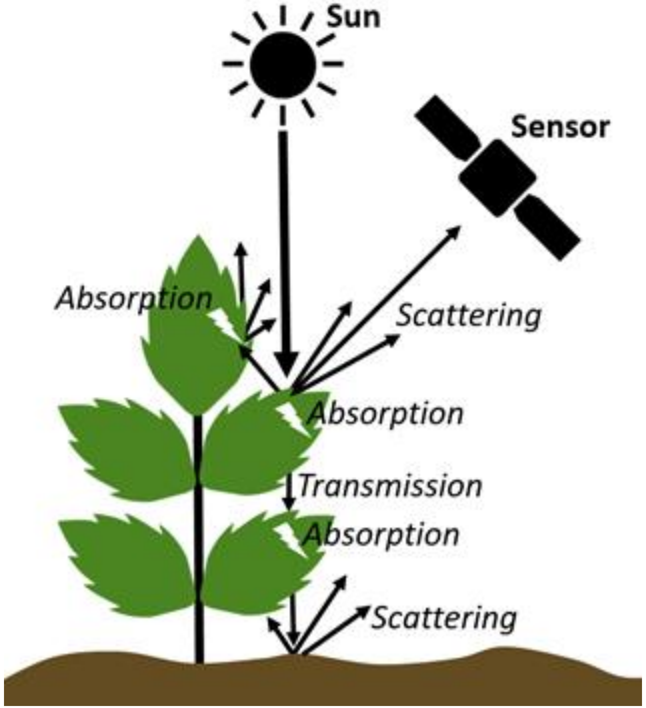
1. A stack of layers, being parallel to each other
1. Inner-layer homogeneity
1. Rough surface, and isotropic scattering

Sail Model - Inputs (W. VERHOEF, 1984, 1985)



Radiative transfer in plant canopies, i.e. transmission, absorption and scattering (Kattenborn, 2018)

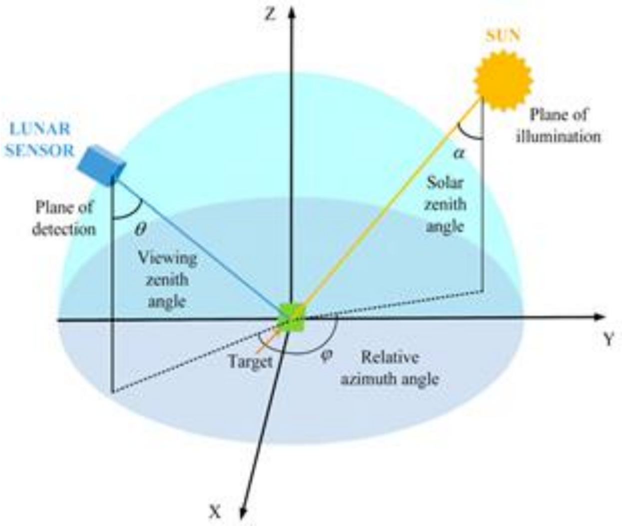
(1) Sail is a Canopy-level RTM that describes the reflectance characteristics (400nm to 2500nm) of Canopy as a function of some biophysical and geometric parameters, i.e.,

Inputs to SAIL:

1. Structural canopy parameters (LAI, mean leaf inclination angle (θ_1))
2. Geometry configuration (zenith and relative azimuth viewing angles (θ_v, ψ_v), zenith solar angle (θ_s))
3. Fraction of diffuse illumination (skyl),
4. and soil spectral reflectance (ρ_s)

Output of SAIL:

Canopy bidirectional reflectance.



Sail Model - Assumptions & Limitations

(Verhoef and Bunnik, 1981,Verhoef2007) :

SAIL considers the canopy as a horizontal, homogeneous, turbid, and infinitely extended vegetation layer composed of diffusely reflecting and transmitting elements.

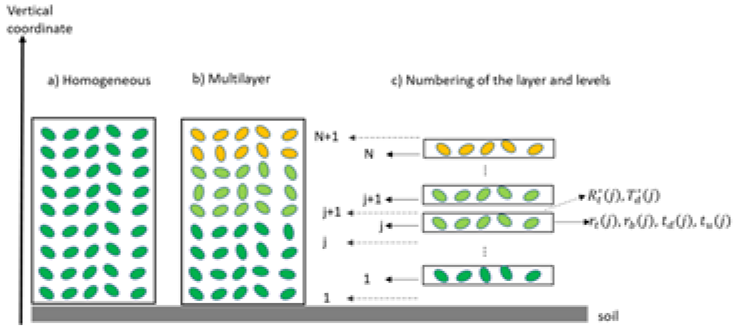


Figure 2. Homogeneous (**a**) and multi-layer canopies with vertical heterogeneity of leaf optical properties and orientations (**b**). Numbering the layers (solid arrows) and flux levels (dashed arrows) for applying the four-stream theory to multi-layer canopies (**c**).

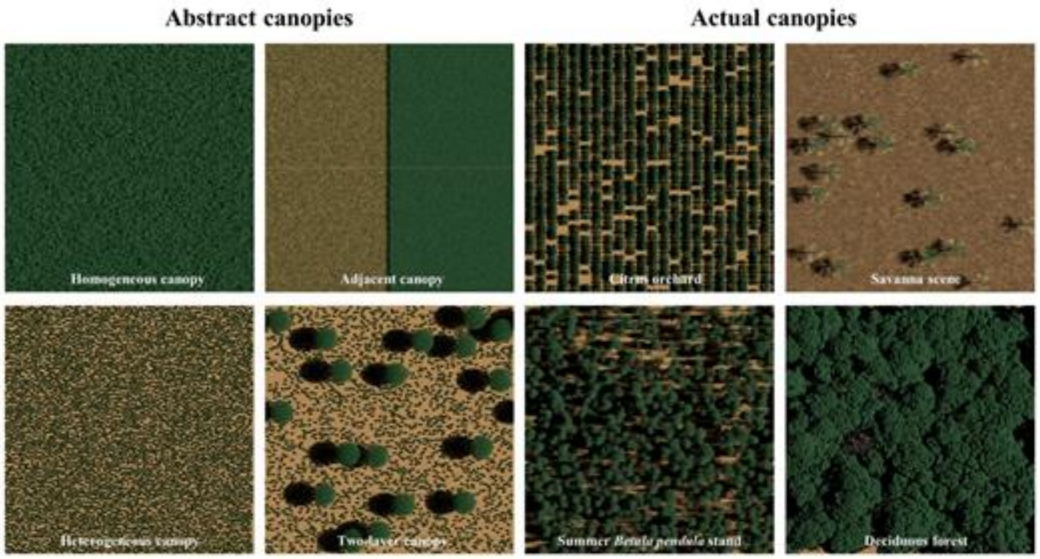
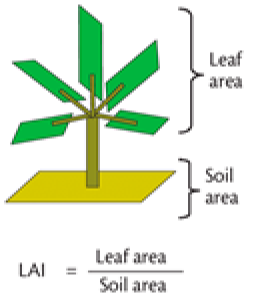
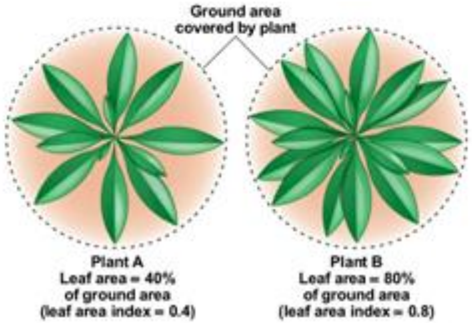
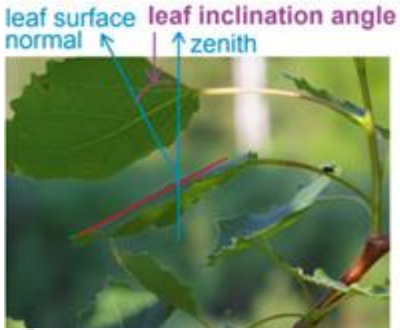


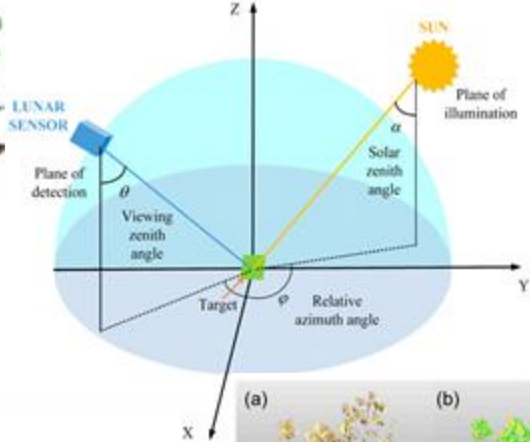
Fig. 2. Typical canopies from RAMI-V forest scenes (https://rami-benchmark.jrc.ec.europa.eu/_www/phase_descr.php?strPhase=RAMI5). These images are simulated with LESS model at a resolution of 0.1 m for visualization.

LAI, leaf inclination angle, Fraction of diffuse illumination, Zenith Solar Angle, **Zenith view angle, and Relative Azimuth angle**









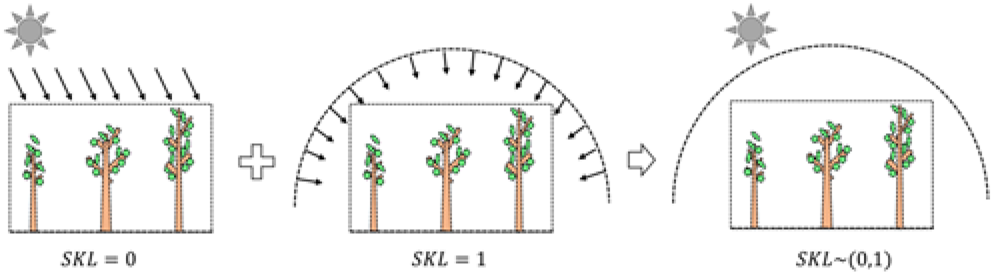


Fig. 3. The simulation of the BRF with different fractions of diffuse radiation. The BRF under arbitrary SKL is obtained by the weighted combination of $BRF_{SKL=0}$ and $BRF_{SKL=1}$.

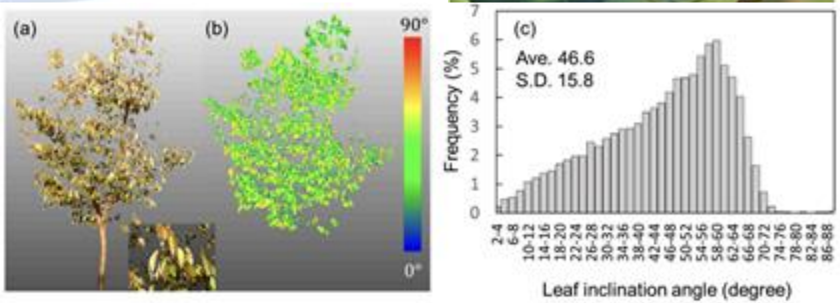
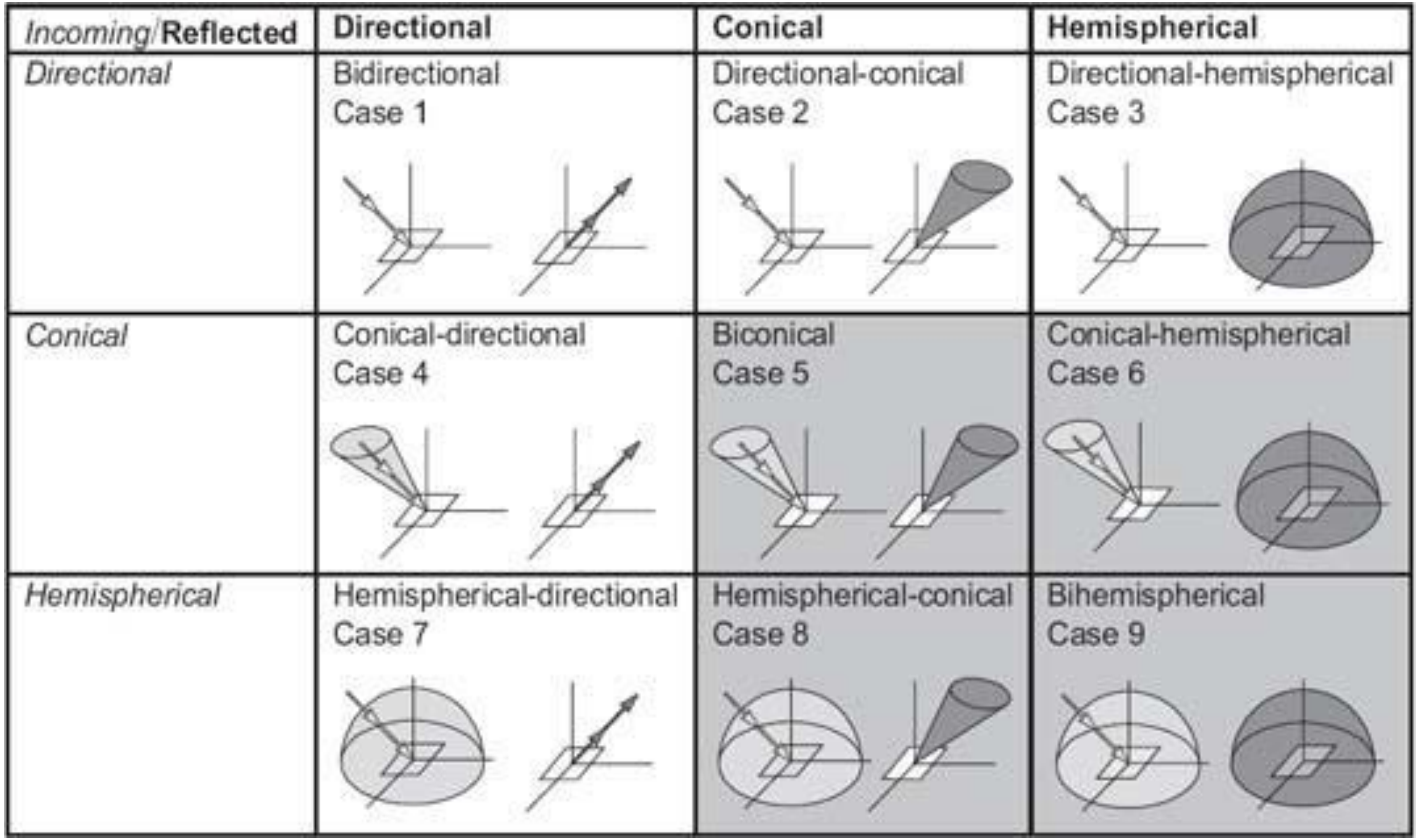


Figure 9. Distribution of leaf inclination angle within a tree (cherry blossom). Panel **(a)** shows reconstructed 3D image obtained from lidar. Panels **(b)** and **(c)** show distribution map of leaf inclination angle and its distribution, respectively.

Which one for SAIL?



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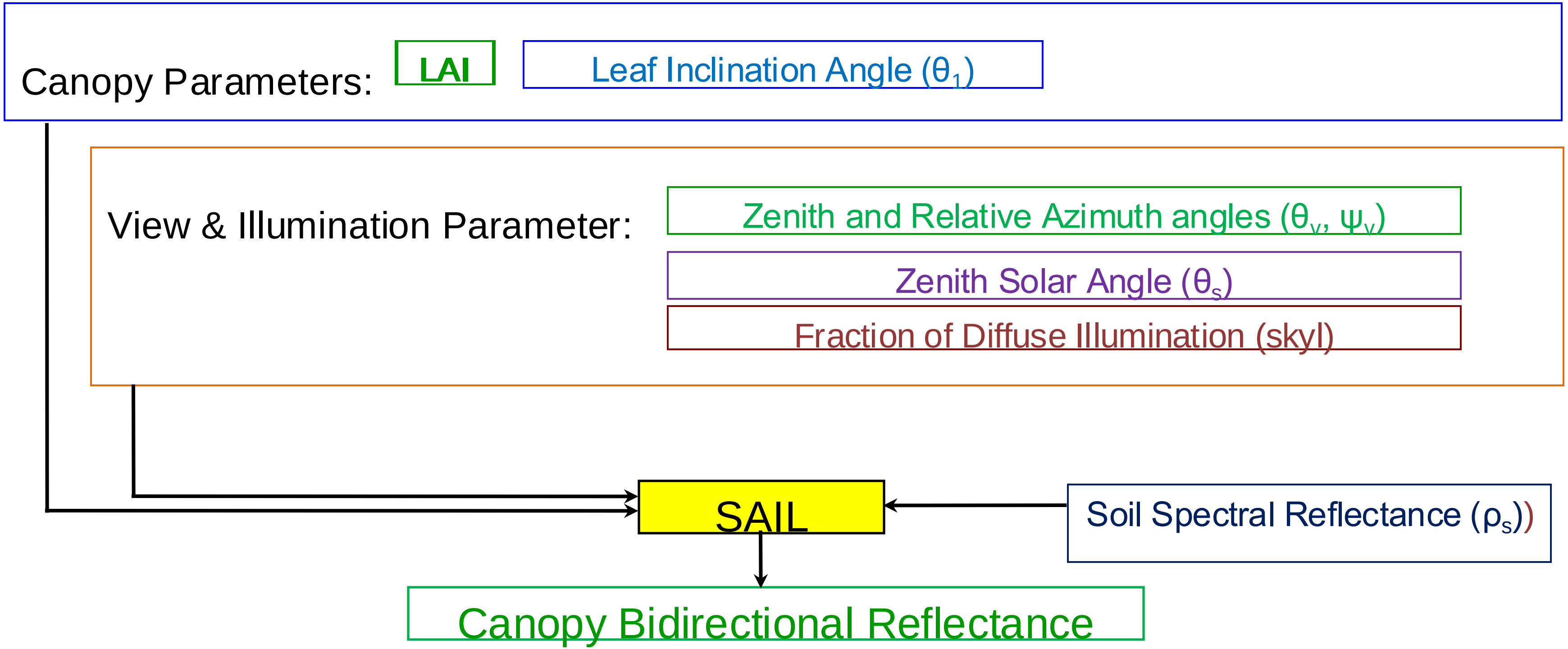
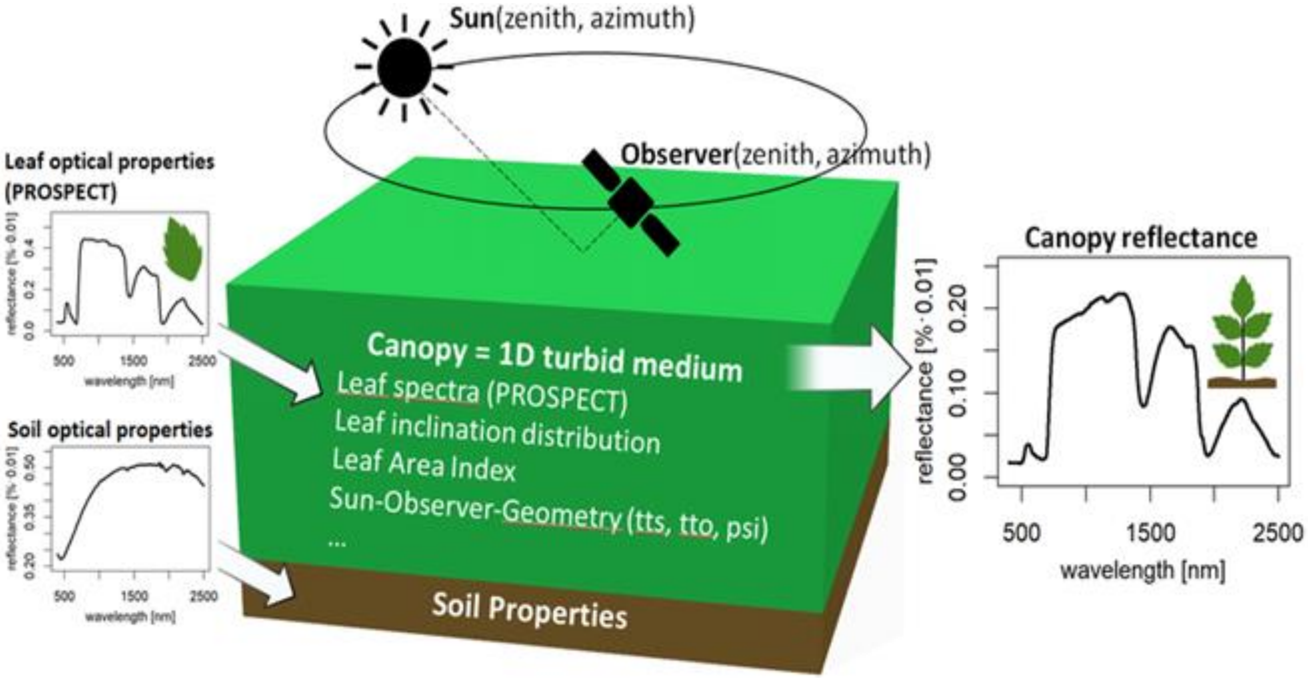
Sail:


Canopy Parameters:
LAI
Leaf Inclination Angle (θ_1)
View & Illumination Parameter:
Zenith and Relative Azimuth angles (θ_v, ψ_v)
Zenith Solar Angle (θ_s)
Fraction of Diffuse Illumination (skyl)
SAIL
Soil Spectral Reflectance (ρ_s))
Canopy Bidirectional Reflectance

Prosail = Prospect + Sail (Verhoef et al. 2007)



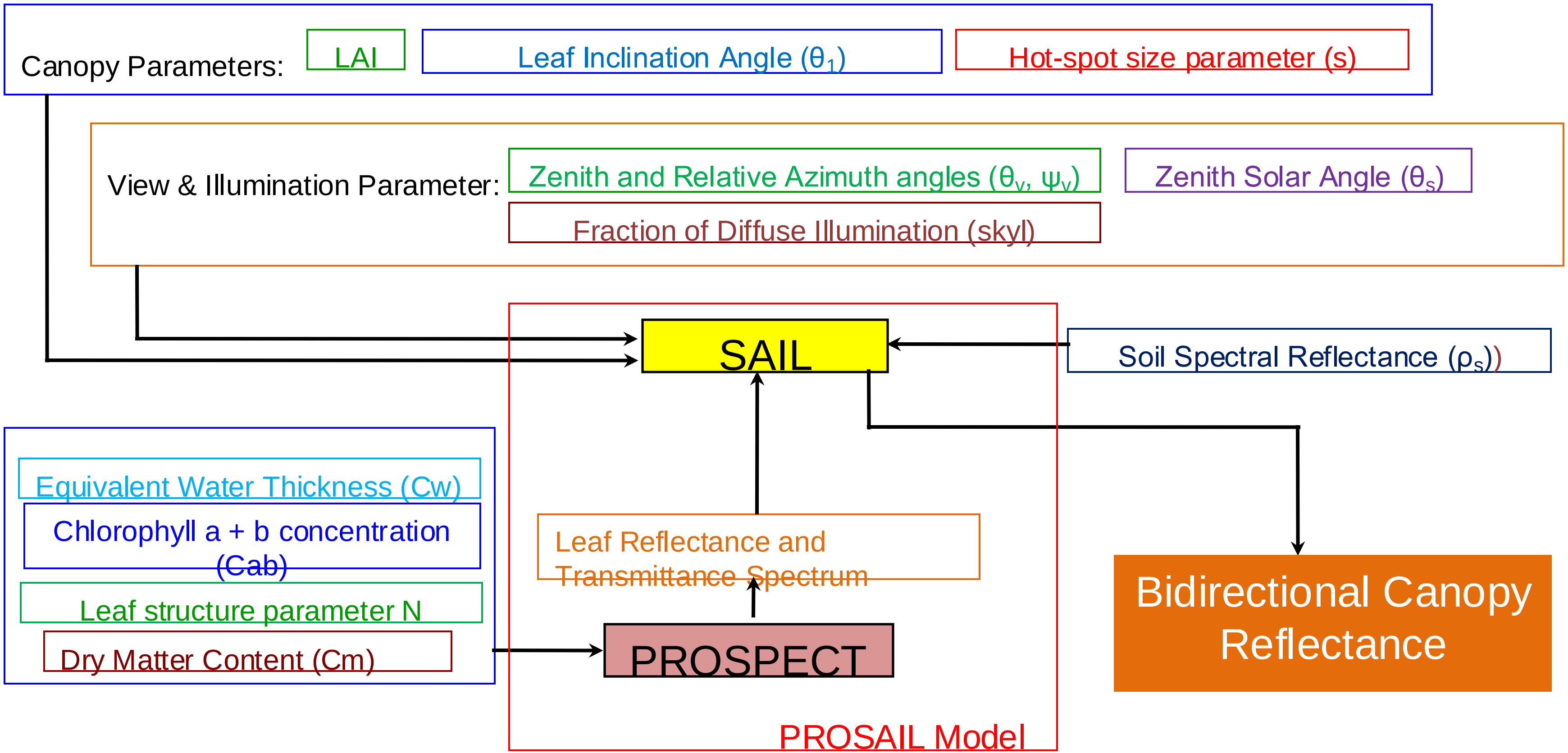
Prosail = Prospect + Sail (Kattenborn, 2018)

(1) Prosail integrates Prospect into Sail to link Canopy-level RTM with leaf-level RTM;

(2) Prosail has 14 input parameters, including both biochemical and biophysical parameters;

(3) Prosail outputs the bidirectional reflectance of canopy, from 400 to 2500 nm in 1 nm increments.

Prosail = Prospect + Sail



Inputs of Prosail

There are 14 input parameters to PROSAIL model:

1. Chlorophyll a + b concentration (Cab) (µg/cm2): Measured using DMSO (Dimethyl Sulphoxide).

2. **Equivalent Water Thickness (Cw) (cm):**

Cw = (Fresh weight of leaf (gm) – dry weight of leaf (gm))/Area of leaf (cm^2)

3. **Dry Matter Content (Cm) :**

Cm = Dry weight of leaf / Area

4. **hSpot:**

hspot = Leaf length / Leaf height.

5. **Car (µg.cm-2):** carotenoid content.

6. **Cbrown:** brown pigment content.

7. **N:** Structural Coefficient (unit less)

Inputs of PROSAIL

8. **Leaf Area Index (LAI):** Leaf area per unit ground surface area. Structural Coefficient (unit less).

9. **Average leaf angle (angl):** description of the angular orientation of the leaves.

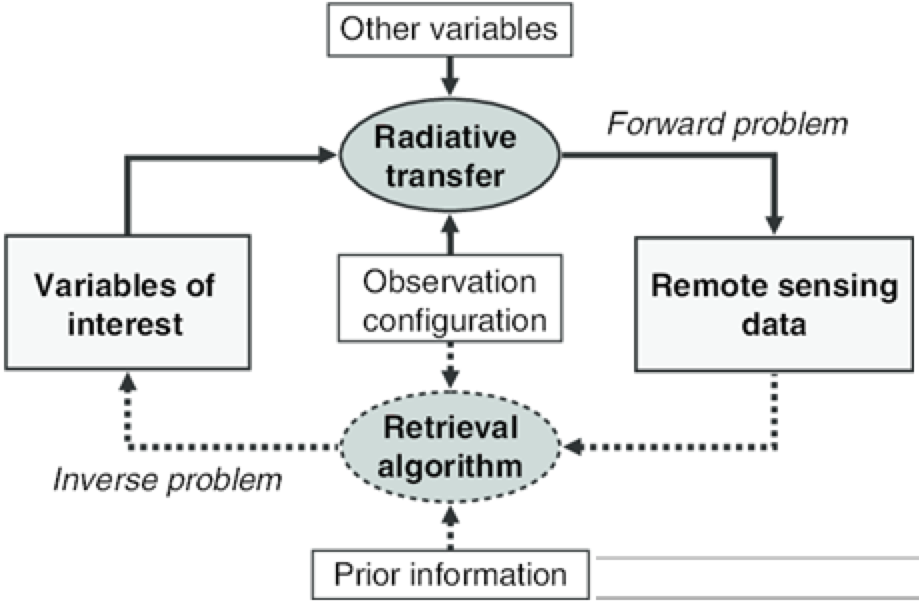
10. **Soil coefficient (psoil):**

11. **Diffuse/direct radiation (skyl)**

12. **Solar zenith angle (tts):** Angle between sun position and with respect to zenith

13. **Observer zenith angle (tto):** Angle between observer (sensor) position and with respect to zenith.

14. **Azimuth (°) (psi):** Angle between observer (sensor) position with respect to north.



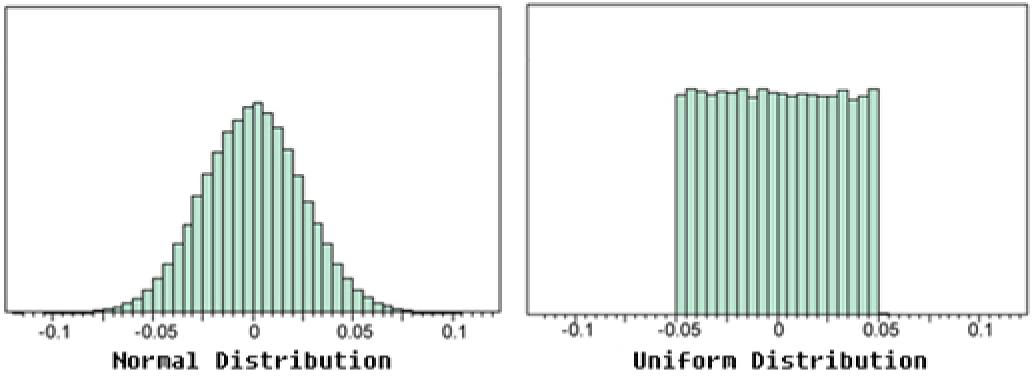
Why forward model (e.g., Prosail) is important?

Applications	Exemplary References
Forward Modes:	
Simulation of canopy reflectance for diverse vegetation types	[110,111]
Influence of the illumination/observation geometry on spectral reflectance (and vegetation indices)	[41,112,113]
Influence of biophysical and biochemical variables on spectral reflectance (or vegetation indices)	[37,114–116]
Sensitivity of canopy reflectance to leaf optical properties/Global sensitivity analysis (GSA)	[40,42,67,117,118]
Design, test and adaptation of vegetation indices	[69,119–124]
Assimilation of simulated reflectance/vegetation indices into crop growth/vegetation dynamic models	[125–130]
Emulation of canopy reflectance	[118,131,132]
Model comparisons	[79,83]
Inverse Modes:	
Biophysical and biochemical variable retrieval	[5,28,39,45,133–138]
Influence of the observation geometry on variable retrieval	[38,139,140]
Determination of phenology	[44,75]
Assimilation of retrieved products into water balance models	[76,107]
Simulation and variable retrieval tests for future missions	[38,45,87,96]

Prosail Simulation - how to simulate data?

TABLE I: Ranges of the input variables for the PROSAIL model for the generation of the LUT.

Variable	Abbr.	Unit	Min	Max
Leaf structure parameter	N	Unitless	1	2
Leaf chlorophyll concentration	C_{ab}	μgcm^{-2}	20	70
Dry matter content	C_m	gcm^{-2}	0.004	0.007
Equivalent water thickness	C_w	gcm^{-2}	0.005	0.03
Leaf area index	LAI	m^2cm^{-2}	0.001	6
Average leaf angle	ALA	Deg	30	70
Hot-spot size parameter	hot	mm^{-1}	0.05	1
Soil brightness parameter	$scale$	Unitless	0.5	1.5



Prosail is a forward model:

Y = f(X)

What is Y?

1. Bidirectional reflectance from canopy (400nm - 2500nm);

What are the factors that constitute X:

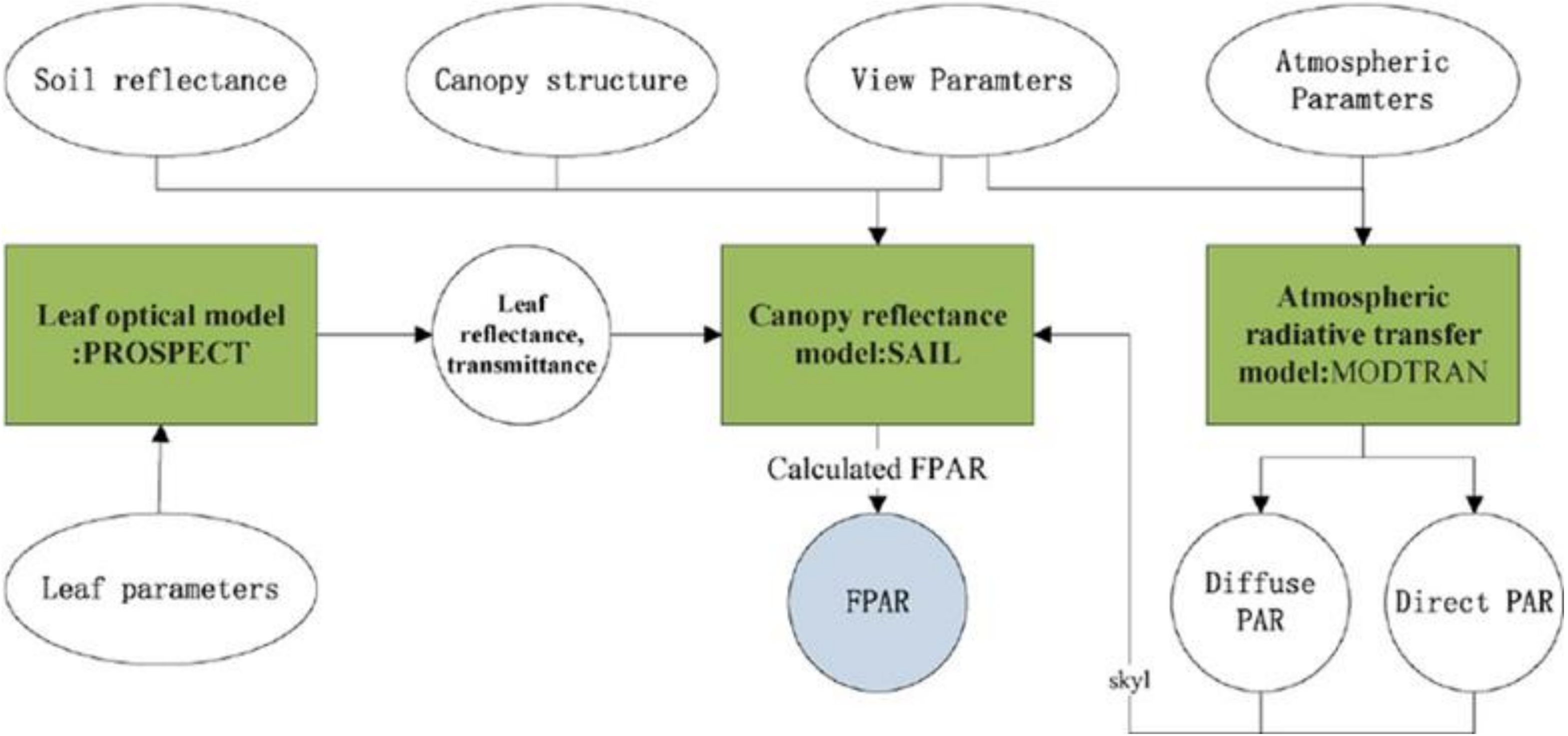
1. A total of 14 input parameters;

How to simulate Y using X?

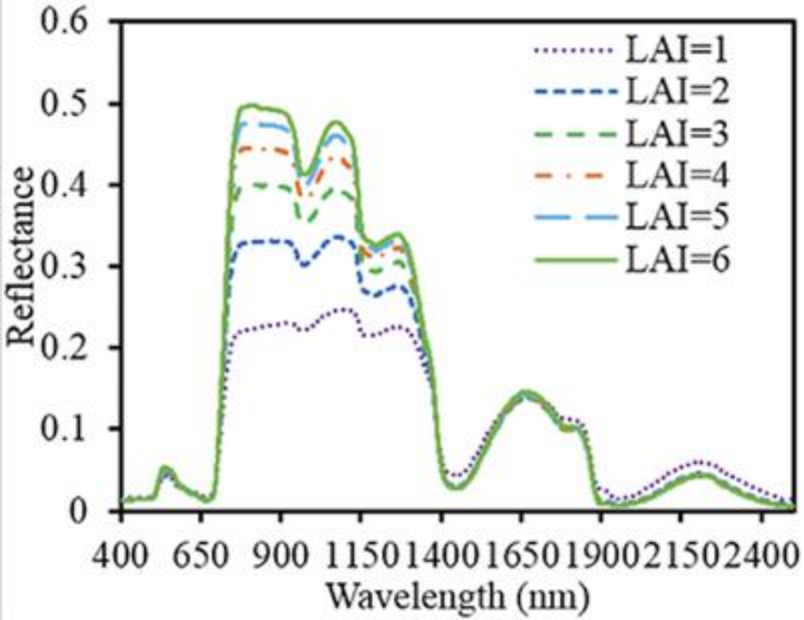
Step 1: know the distribution of X;

Step 2: obtain samples {Xi| i=1,..,N} based on the distribution of X;

Step 3: use {Xi| i=1,..,N} as input to Prosail and generate {Yi| i=1,2,...,N}



A flowchart of the coupled atmosphere – canopy model for describing the process of FPAR (fraction of photosynthetically active radiation) simulation; PROSPECT is Leaf Optical Properties Spectra model, SAIL is the Scattering by Arbitrarily Inclined Leaves Model, MODTRAN is the MODerate resolution atmospheric TRANsmission model, PAR is the photosynthetically active radiation, and FPAR is the fraction of absorbed photosynthetically active radiation (Dong 2016, Sensitivity analysis of retrieving fraction of absorbed FPAR using remote sensing data)

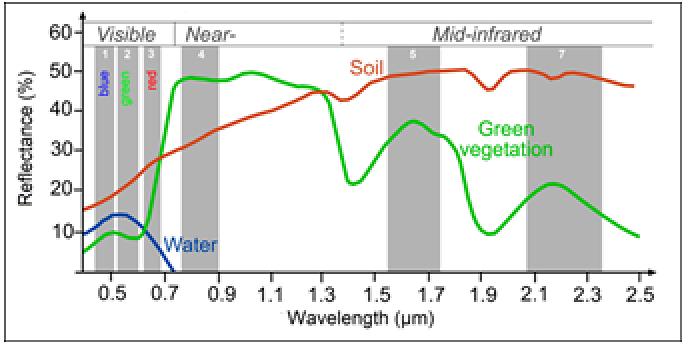


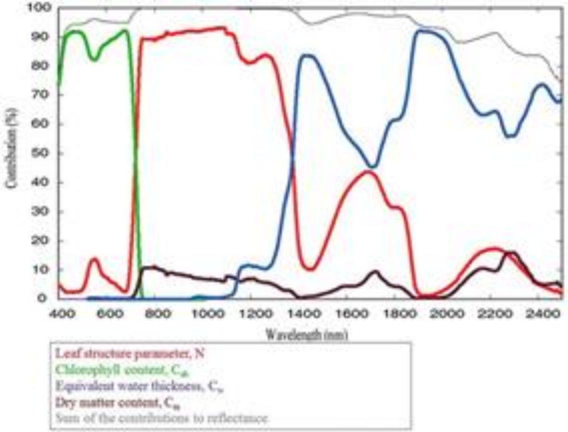
Sensitivity Analysis - LAI

- LAI is dominant in NIR Region i.e. 700-1300 nm.
- Why?

Due to the canopy structural development and multiple scattering which is particularly important at these wavelengths.

- When LAI increases reflectance also increases. Why?
- After a certain increase in LAI value the changes in LAI spectra are very small because of shadow effect of plant leaves.

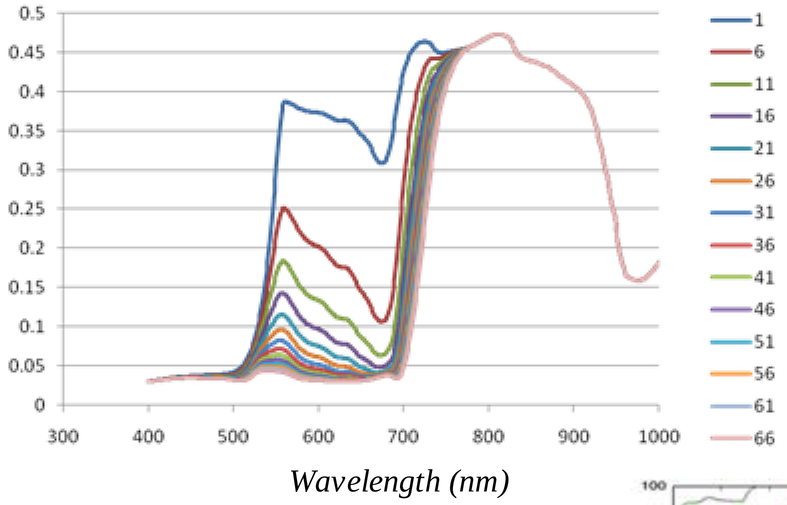




- A inverse effect is noted for SWIR (2000 – 2300 nm) in LAI spectra. Why?

This is because in SWIR region soil reflectance effect is dominant and with increase in LAI (more coverage of ground) the effect of soil reflectance decreases because of canopy shadow effect.

Sensitivity Analysis for Chlorophyll

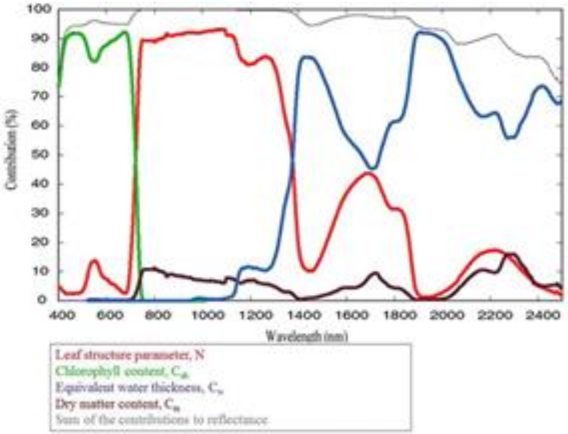


- Chlorophyll radiation is limited to 400 nm to 725 nm.
- Chlorophyll content derives about 60% of reflectance variation in visible range.
- Highter chlorophyll value, lower the reflectance and vice versa. Why ?

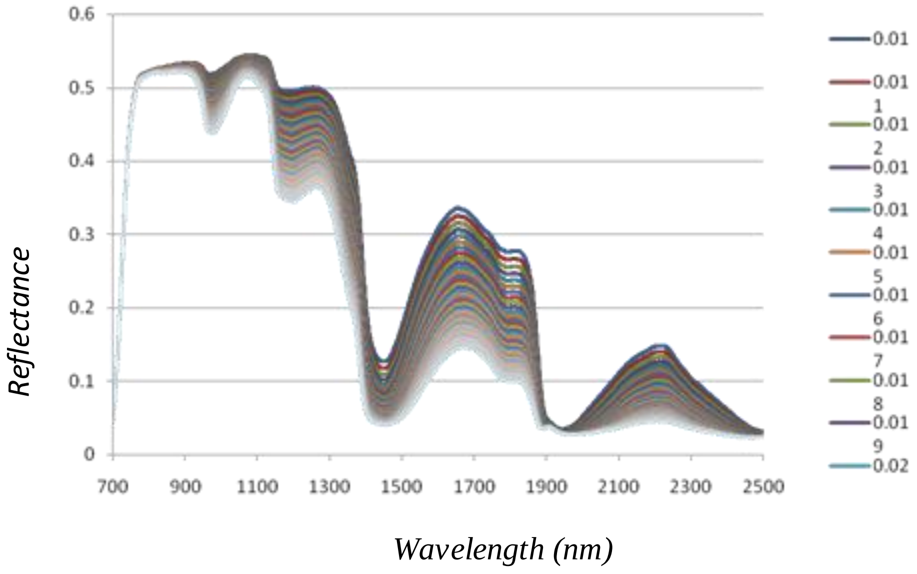
Increase in chlorophyll results in high absorption of sun light and hence lower reflection.

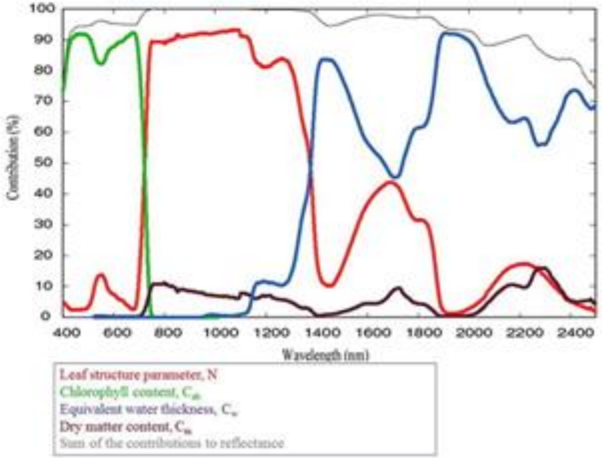
Decrease in chlorophyll pigments results in lesser absorption of sun light and high reflectance.

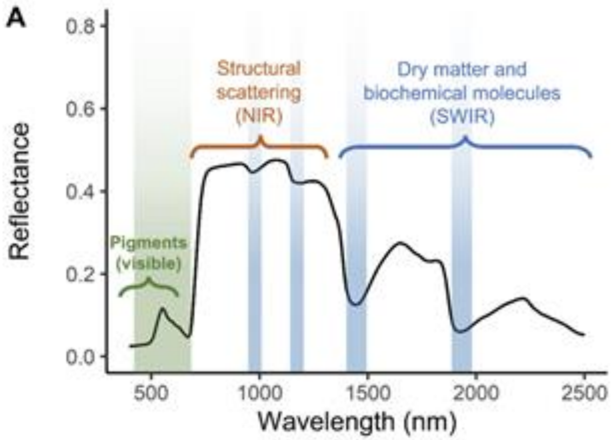
Combined effects of LAI and Chlorophyll occur over the red edge region where LAI and chlorophyll density increase contribute to the shift of the red edge position.



Sensitivity Analysis for Water Content *(Cw)*

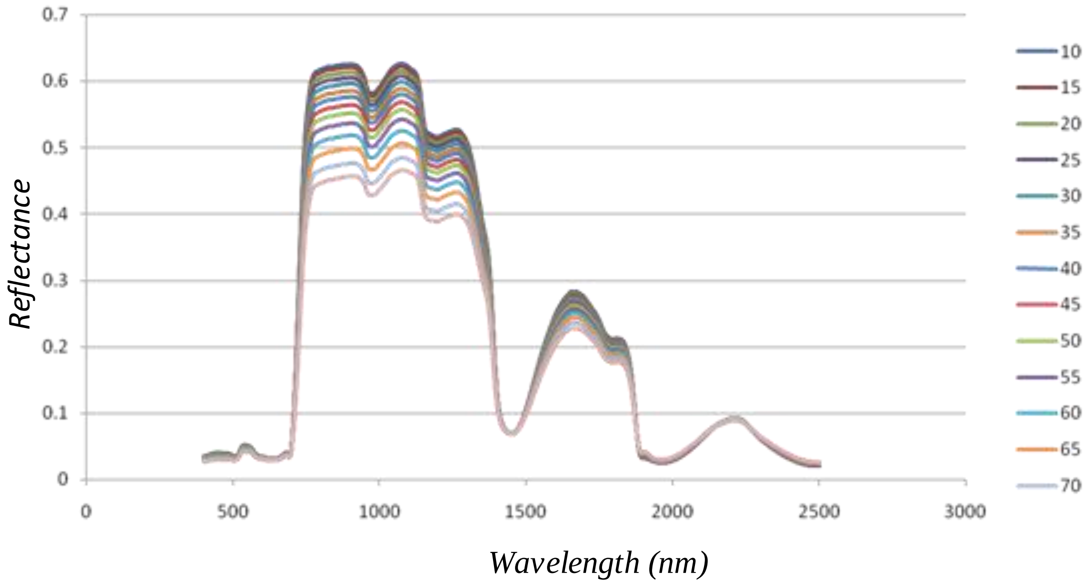


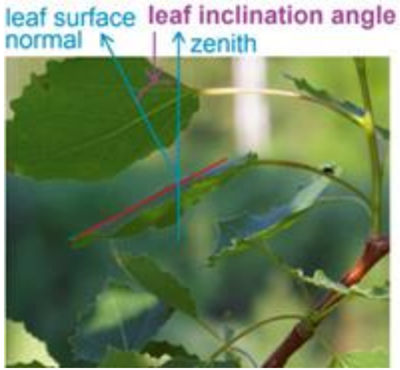


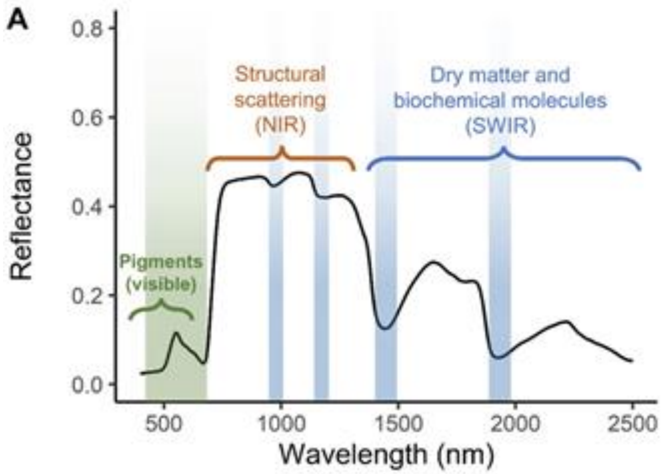


- Water content is a dominating factor in SWIR region of Vegetation Spectrum.
- Higher the water content value lower the reflectance.

Sensitivity Analysis for Leaf Angle







1. Sensitive in the NIR region,
2. As leaf angle increases the reflectance decreases in NIR region

Sensitivity Analysis for Leaf Structure Parameter (N)

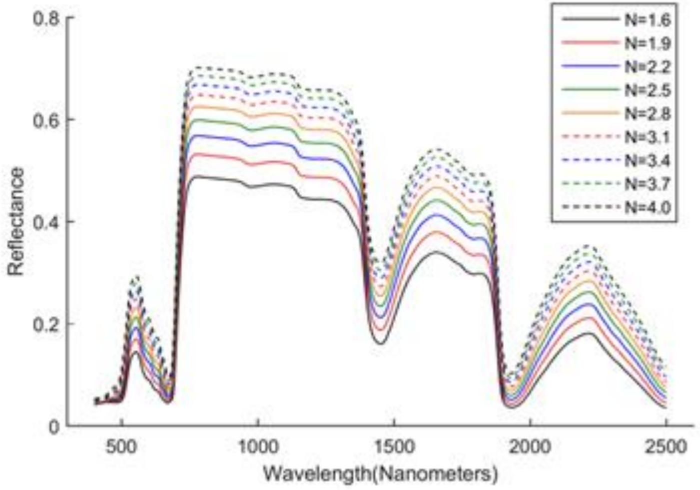
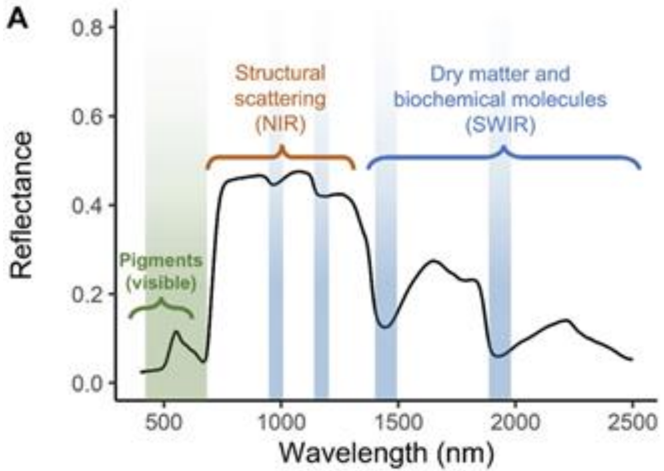


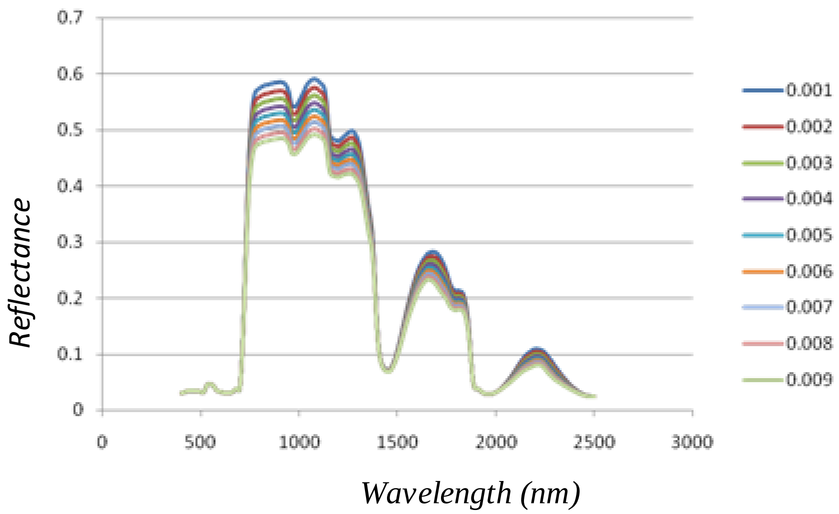
Figure 4. The modeled reflectance generated by PROSPECT-5 with different N. (C_{ab}, C_{car}, C_w, and C_m are fixed as 33 μg/cm², 8.6 μg/cm², 0.012 cm, 0.005 g/cm², respectively).

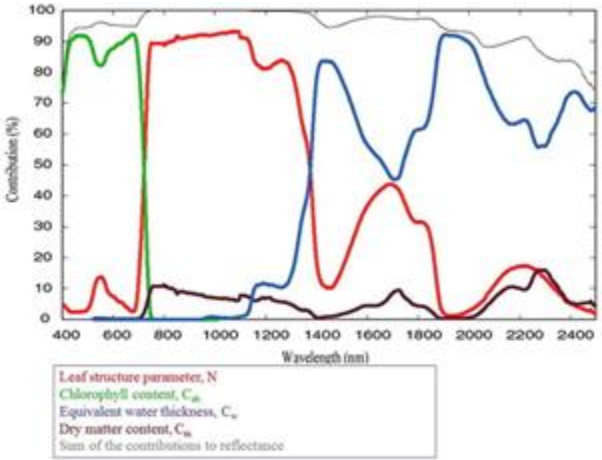
The PROSPECT model regards the leaf as N homogeneous compact layers of plates separated by (N−1) layers of air. The leaf structure parameter (N) describes the leaf mesophyll structure and increases with a more disorderly cell arrangement.

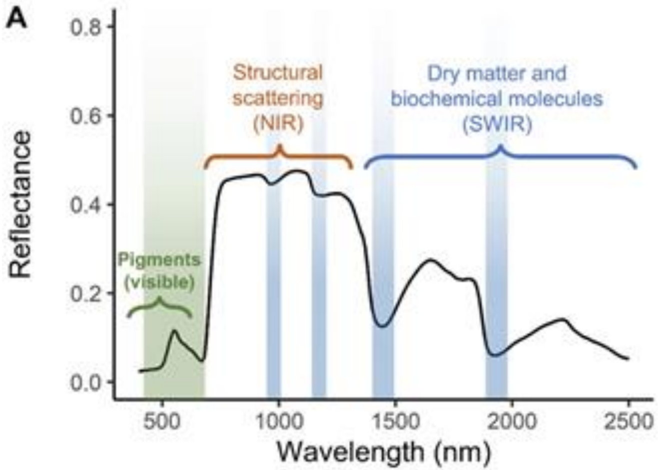
As N increases, the reflectance also increases



Sensitivity Analysis for Dry Matter Content *(Cm)*



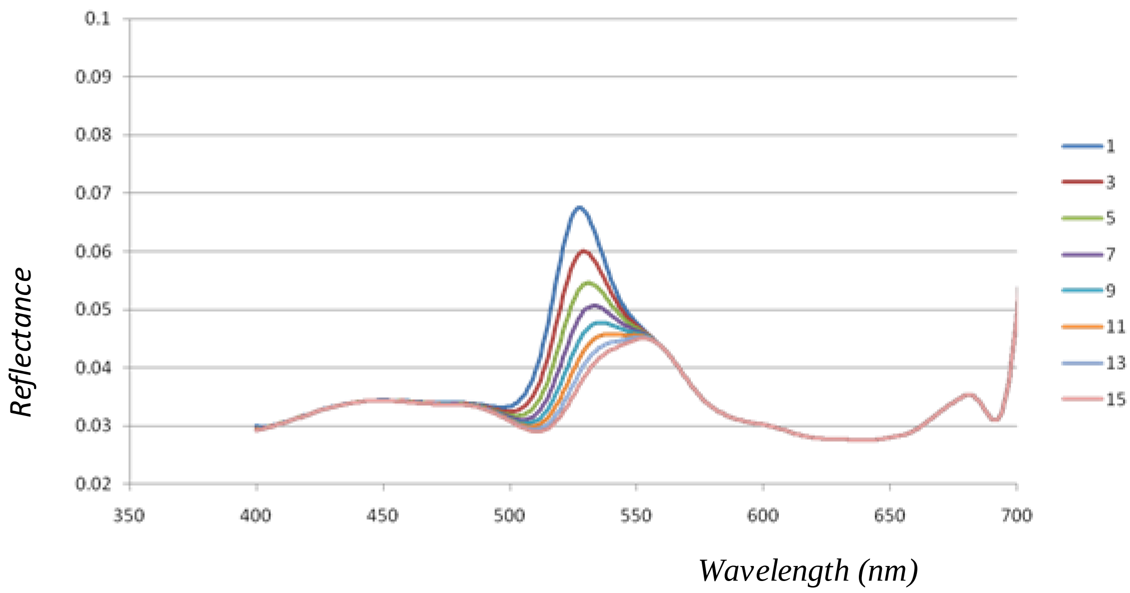




Higher the value lower the reflectance.

Cm= Dry weight/Leaf Area

Sensitivity Analysis for Carotenoid



- When Carotenoids increases reflectance decreases.
- Spectral variation for different ranges of carotenoids has been noticed for 500nm -560nm.

Inversion of PROSAIL

There are various inversion strategies have been proposed. They are :

✓ **Numerical optimization methods** *(Bicheron and Loroy, 1999; Goel and Thompson, 1984).*

✓ **Look Up Table based approaches** (Combal *et al.*, 2002; Knyazikhin *et al*, 1998; Weiss *et al.*, 2000)

✓ **Artificial Neural Networks** (Atgberger *et al*, 2003a ; Baret *et al*, 1995; Weiss *et al.*, 2000, https://step.esa.int/docs/extra/ATBD_S2ToolBox_L2B_V1.1.pdf)

✓ **Principal Component Inversion technique** (Satapathy and Dadwal, 2005)

✓**PEST algorithm**

✓**Support vector machines regression:** (Durbha et al., 2007).

✓**Genetic Algorithm (GA):** Jin and Wang, 1999.

Questions?