RTMs

Uncertainty and spatial diversity

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Layout

1. Leaf RTM
2. Canopy RTM
3. Reflectance factors

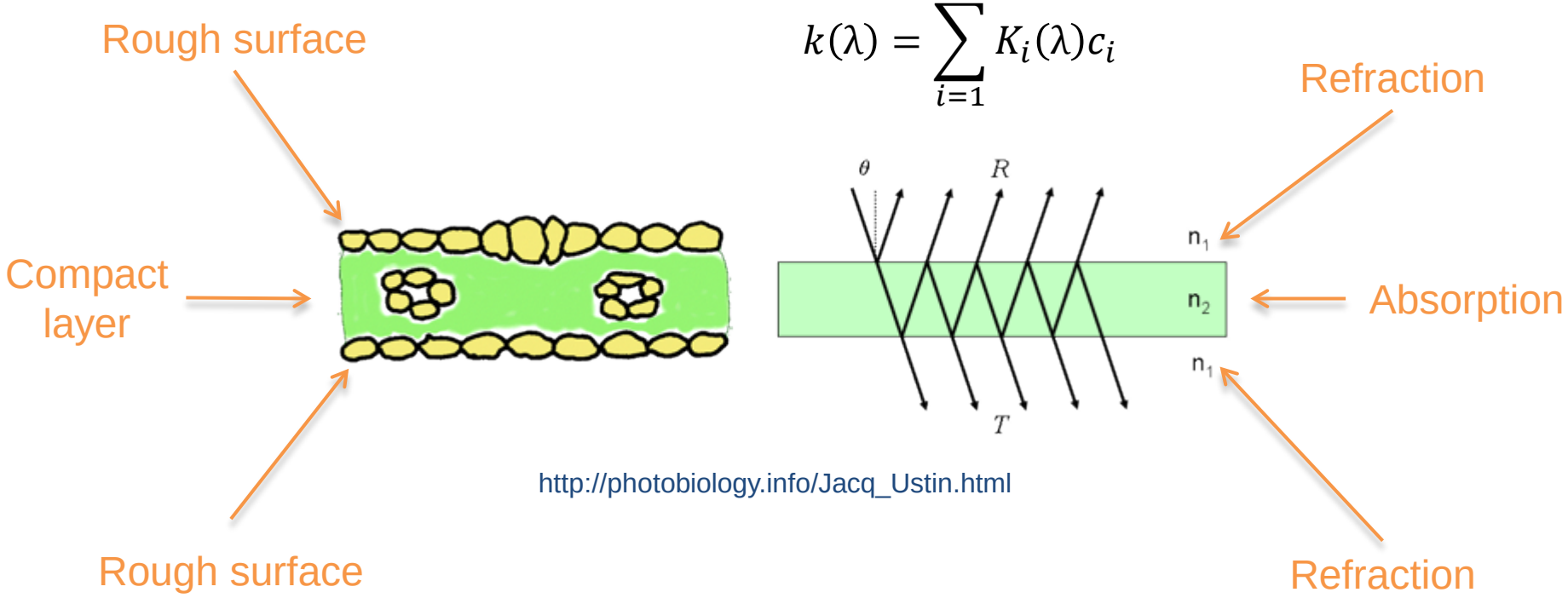
1. LEAF RTM

- **PROSPECT** (Jacquemoud and Baret, 1990)
  - Leaf RTM
    - Inputs
      - Leaf structural parameter (N)
      - Content of absorbents (pigments, water, dry matter)
    - Outputs: Hemispherical-Directional Reflectance (ρ) and Transmittance factors (τ)
    - Plate model (Allen 1969)
      - Semi-transparent layers, parallel plane surfaces
      - Isotropic light (Hemisph.) ~ rough surfaces

1. LEAF RTM

- Simple case. Single layer (~monocots)
  - $N = 1$

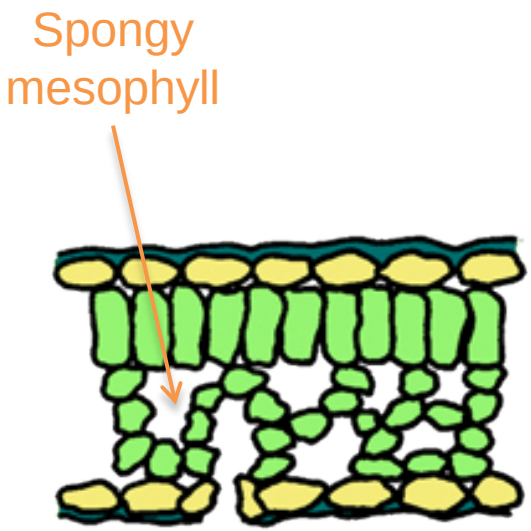
$$k(\lambda) = \sum_{i=1}^{n} K_i(\lambda) c_i$$

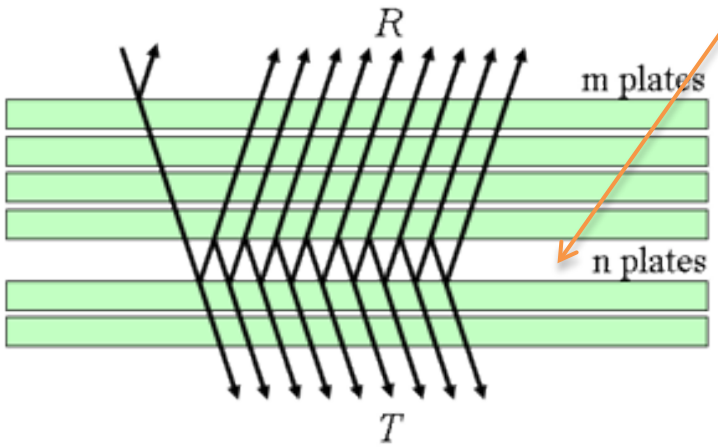


http://photobiology.info/Jacq_Ustin.html

1. LEAF RTM

- Complex case. Multi-layer (dicots, senescent…)
  - $N > 1$; $N \in \mathbb{R}$





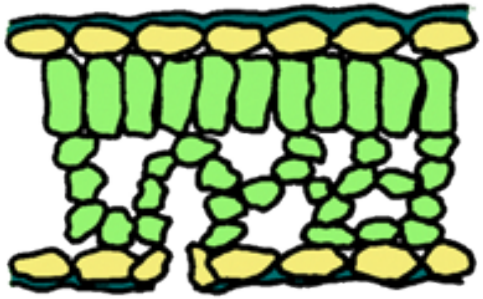
~ Air cavities

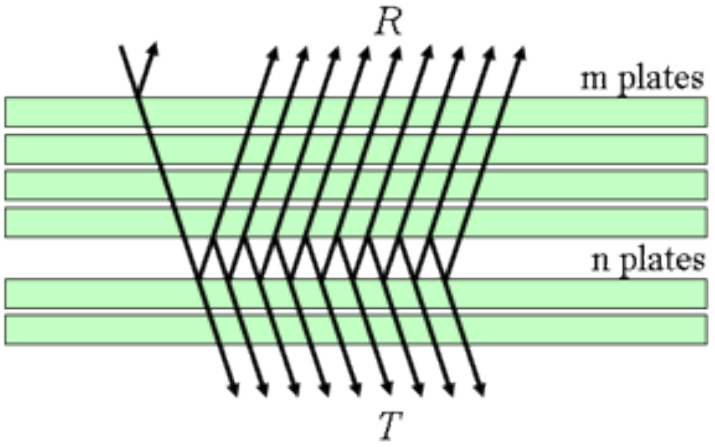
n_{air}
n_{leaf}
n_{leaf}
n_{air}
n_{air}
n_{leaf}
n_{leaf}
n_{air}
n_{air}
n_{leaf}
n_{leaf}
n_{air}

http://photobiology.info/Jacq_Ustin.html

1. LEAF RTM

- Multi-layer leaf model





http://photobiology.info/Jacq_Ustin.html

- Reflected

$$R(m+n) = R(m) + T(m)R(n)T(m) + T(m)R(n)R(m)R(n)T(m) + \ldots$$

$$= R(m) + \frac{T(m)^2 R(n)}{1 - R(m)R(n)}$$

- Transmitted

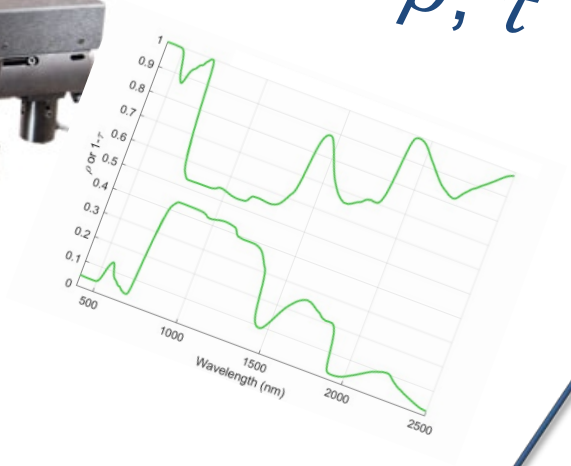
$$T(m+n) = T(m)T(n) + T(m)R(n)R(m)T(n) + \ldots$$

$$= \frac{T(m)T(n)}{1 - R(m)R(n)}$$

1. LEAF RTM

- Determining n_i and K_i? *In vivo*

asdi.com



ρ, τ

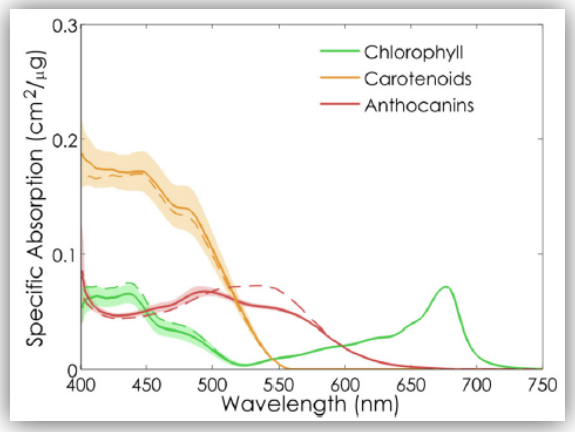
c_i

Model inversion

$$M_{inv}\left(N, \{C_i\}_{i=1:p}\right) = \sum_{\lambda=1}^{n_\lambda} \left(R_{meas,\lambda} - R_{mod,\lambda}\left(N, \{C_i\}_{i=1:p}\right)\right)^2 + \left(T_{meas,\lambda} - T_{mod,\lambda}\left(N, \{C_i\}_{i=1:p}\right)\right)^2$$

Féret et al., 2017

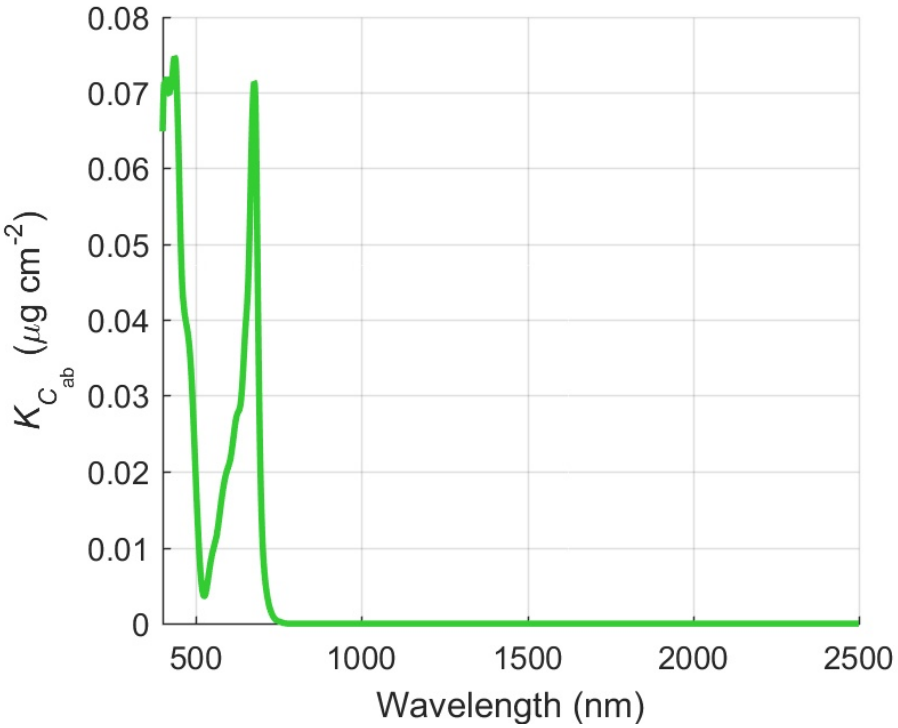
Gonzalez-Cascon, M.R. & Martin, M.P., 2018

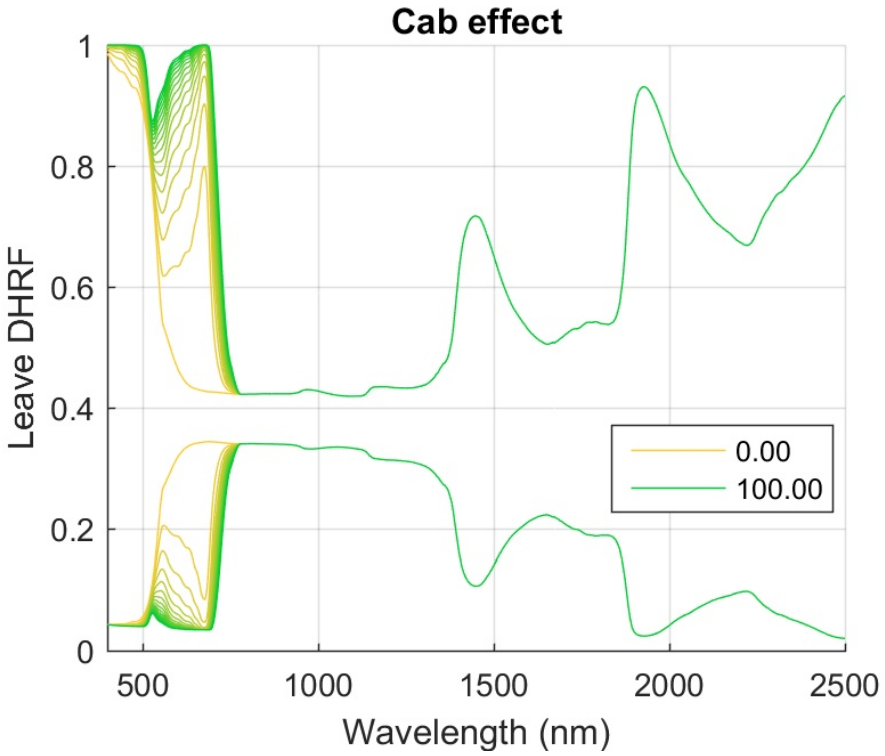


Féret et al., 2017

1. LEAF RTM

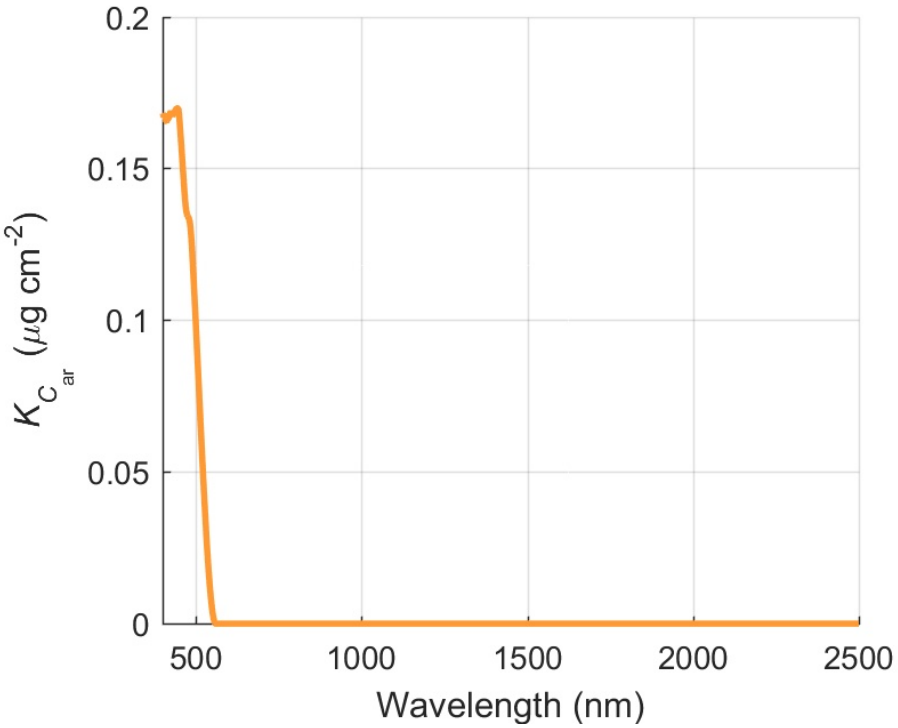
- Chlorophyll a + b

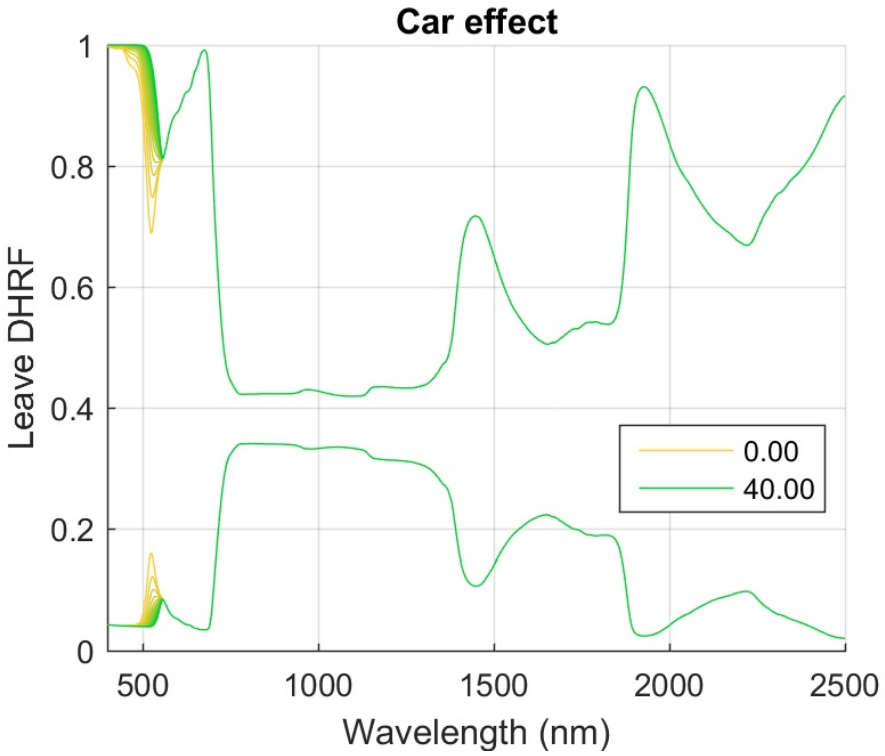




1. LEAF RTM

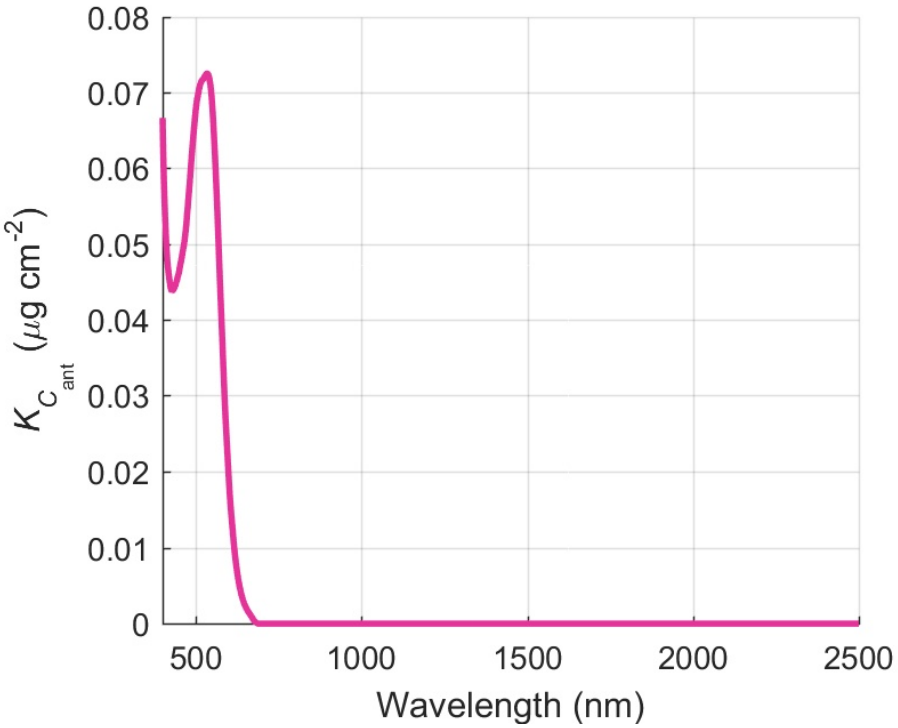
- Carotenoids

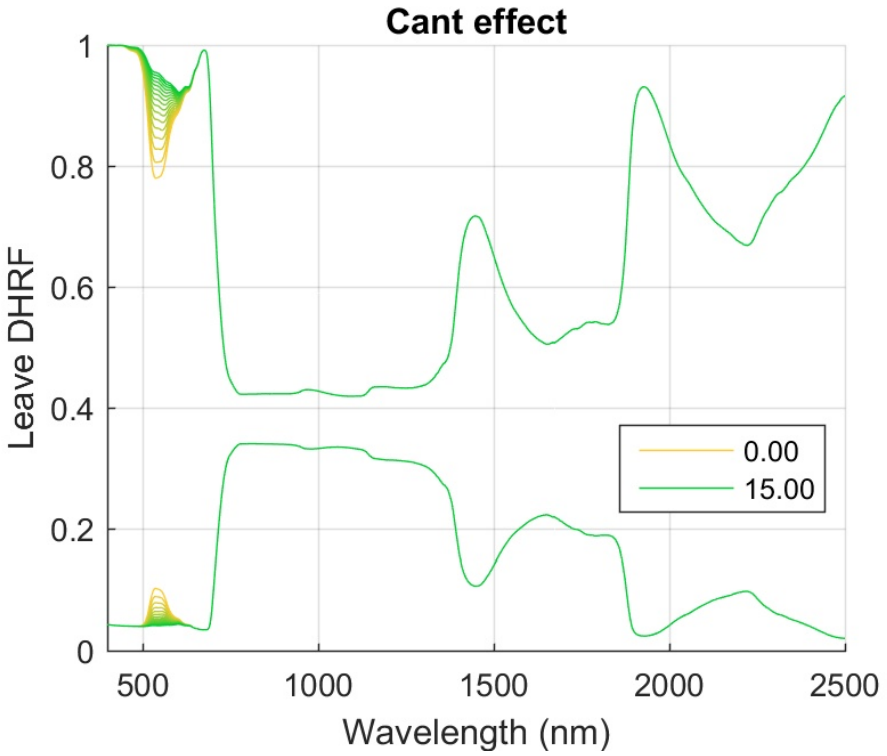




1. LEAF RTM

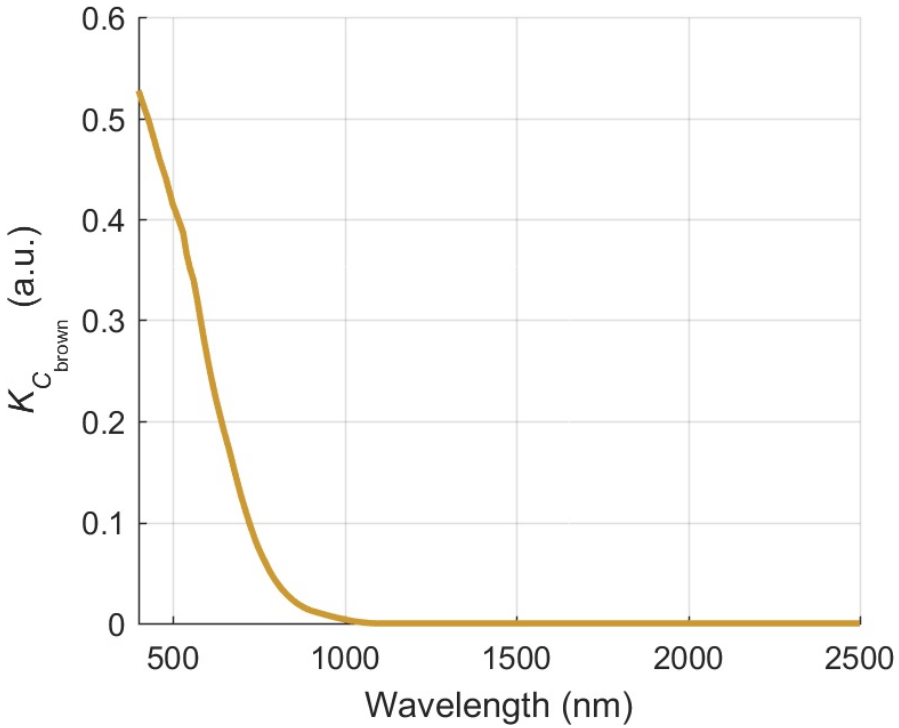
- Anthocyanins

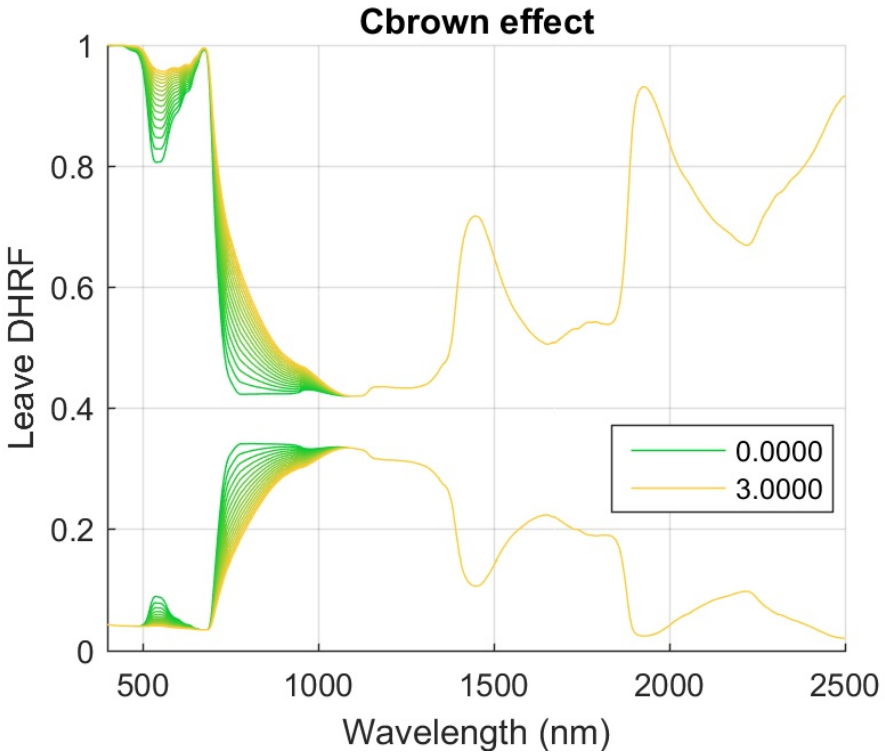




1. LEAF RTM

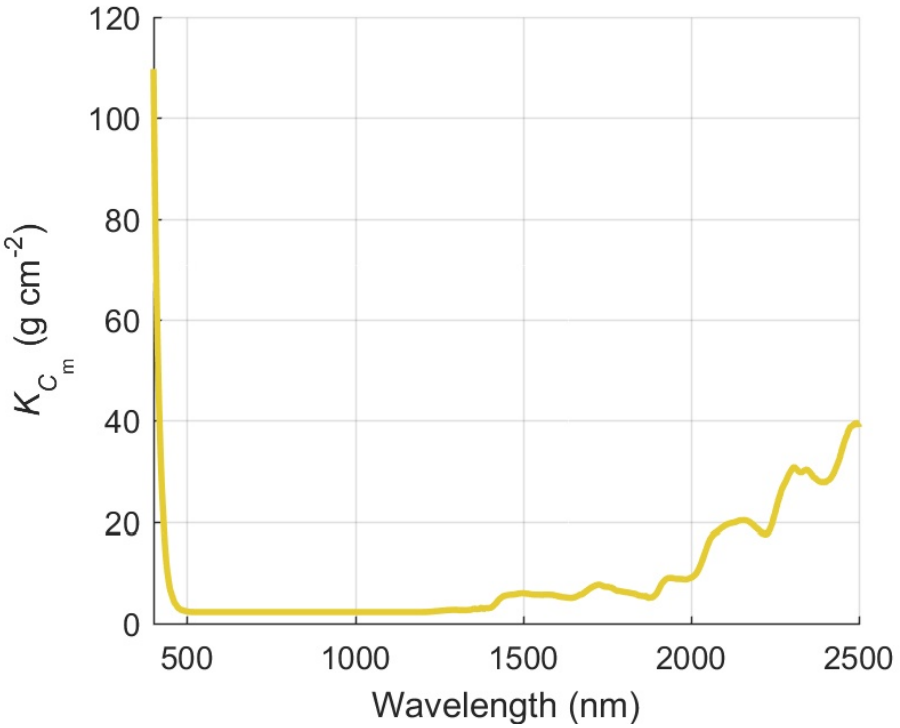
- Brown/senescent pigments

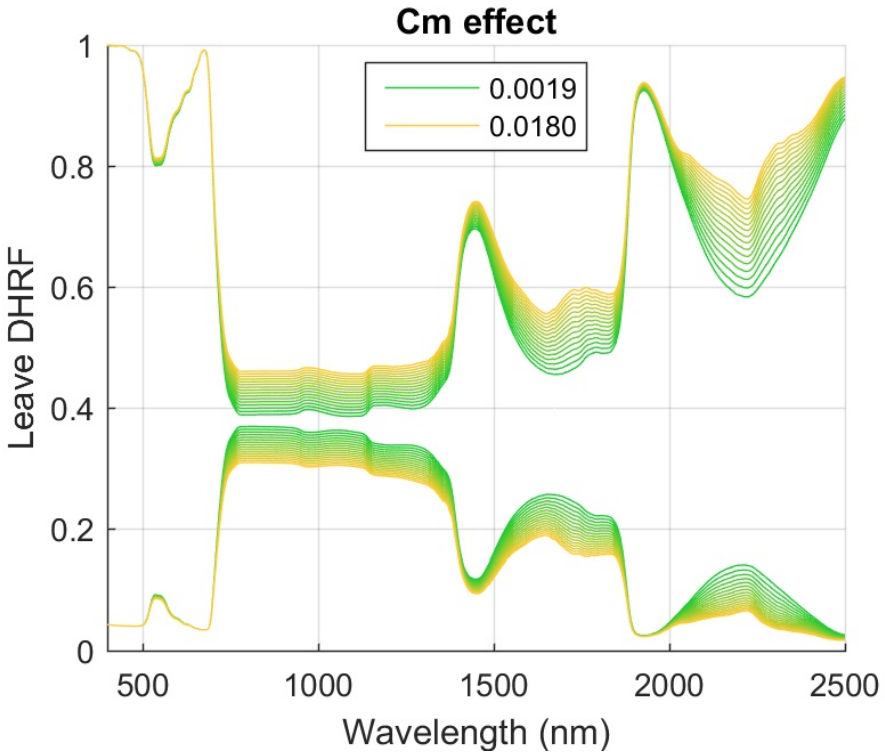




1. LEAF RTM

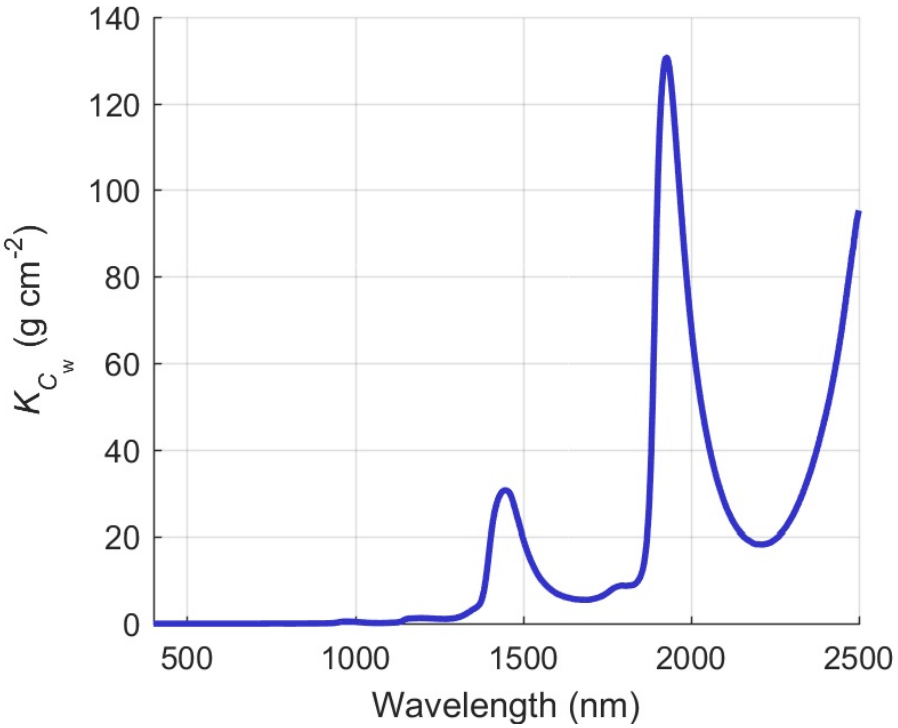
- Dry matter

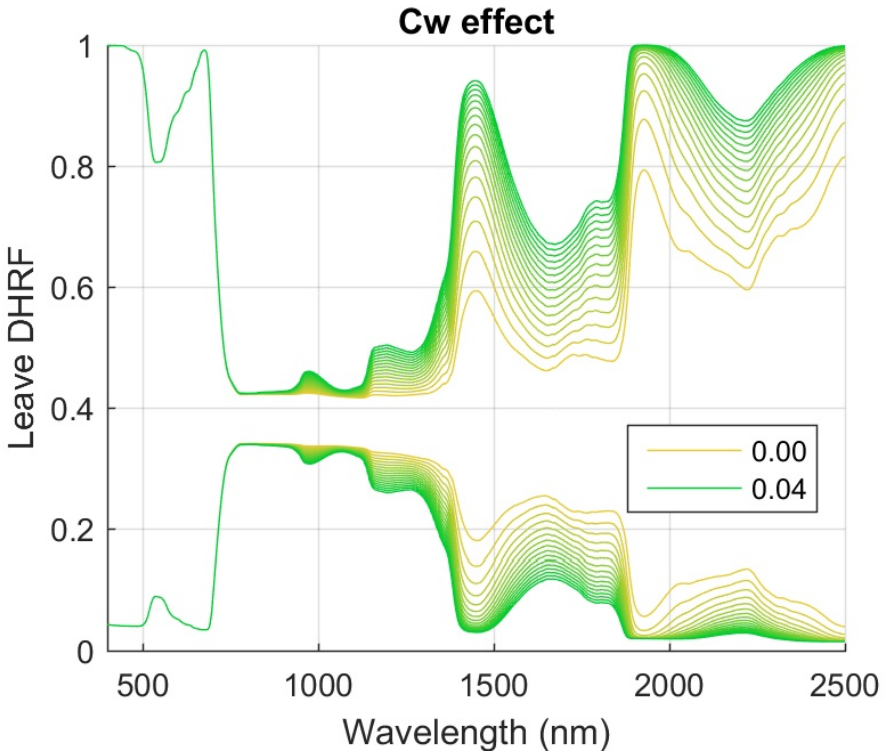




1. LEAF RTM

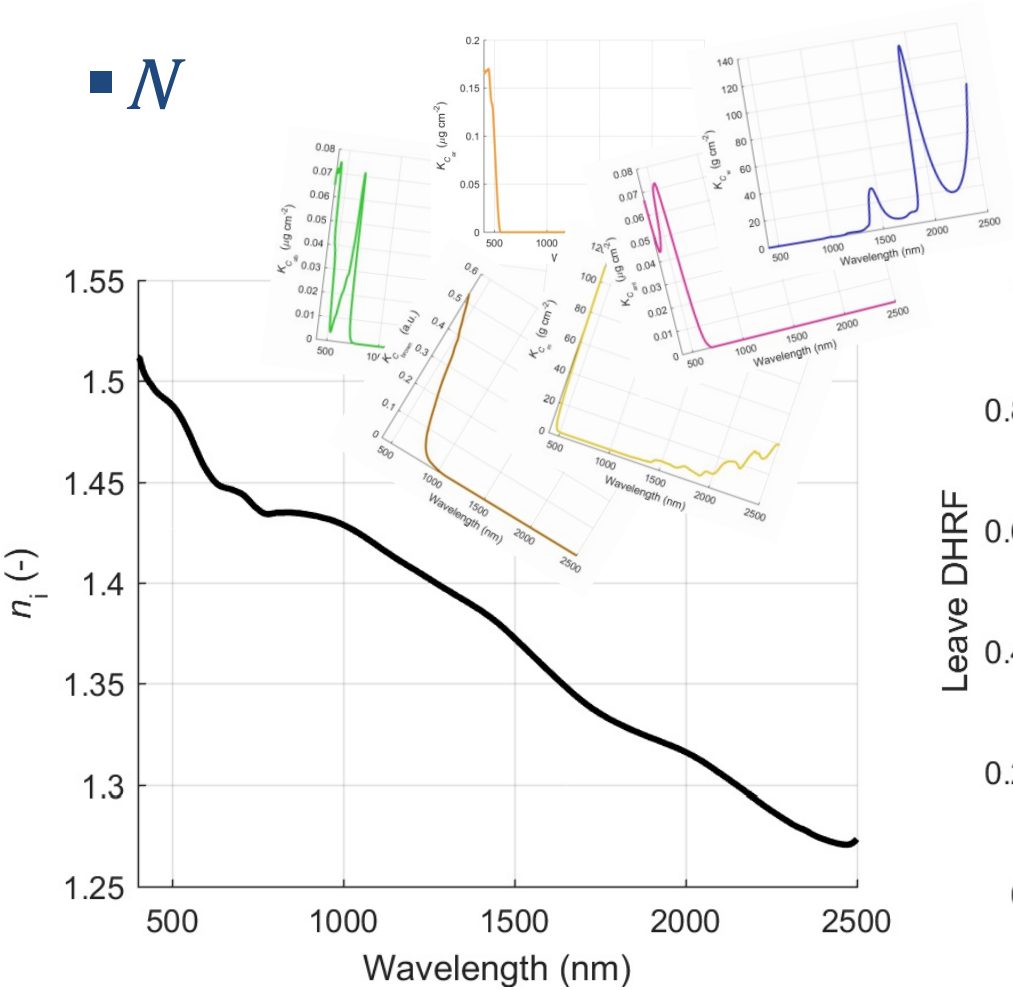
- Water

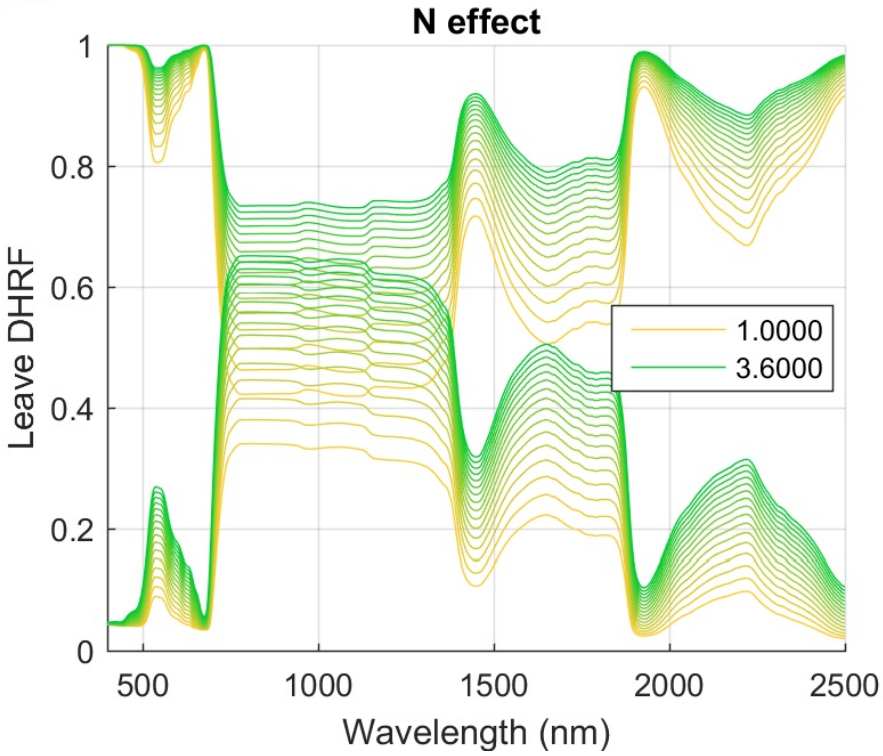




1. LEAF RTM

- N


1.55
1.5
1.45
1.4
1.35
1.3
1.25
n_i (-)
500
1000
1500
2000
2500
Wavelength (nm)


N effect
1
0.8
0.6
0.4
0.2
0
Leave DHRF
1.0000
3.6000
500
1000
1500
2000
2500
Wavelength (nm)

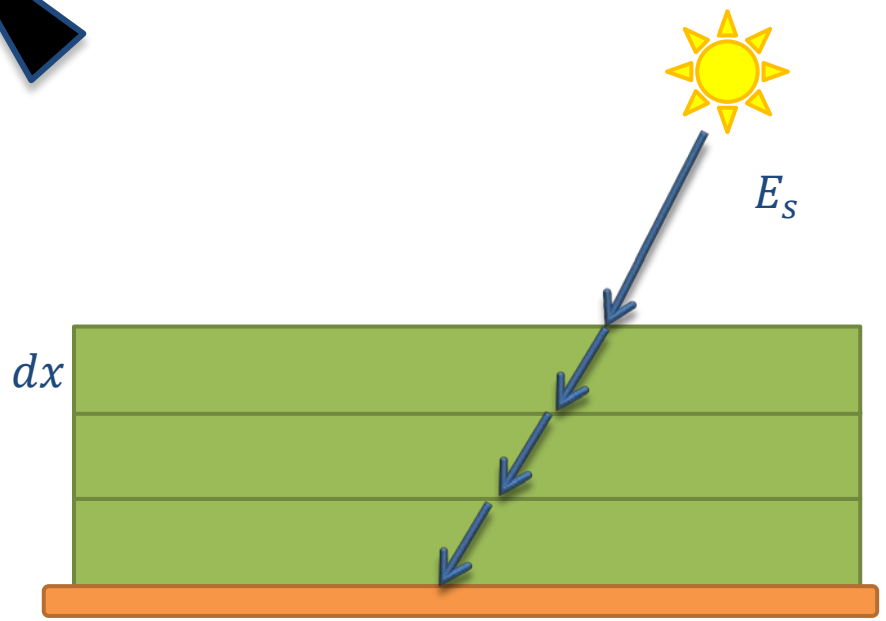
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Extinction coefficient k

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



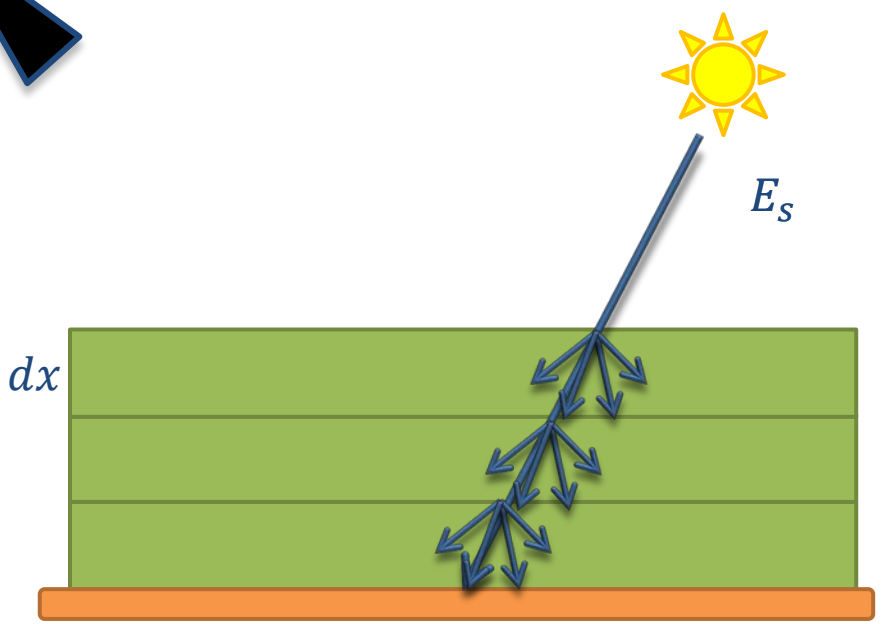
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Forward scattering coefficient s

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



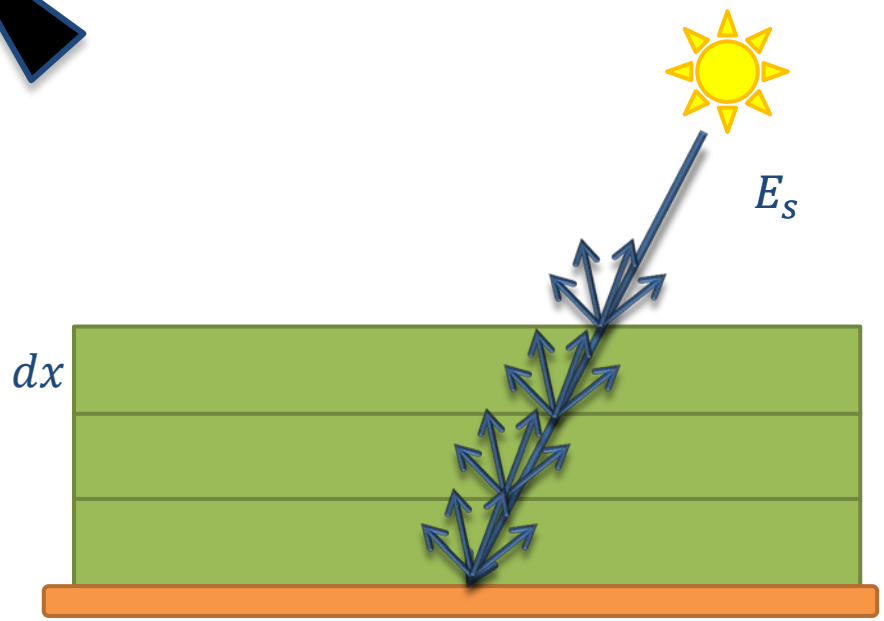
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Backscatter coefficient s'

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



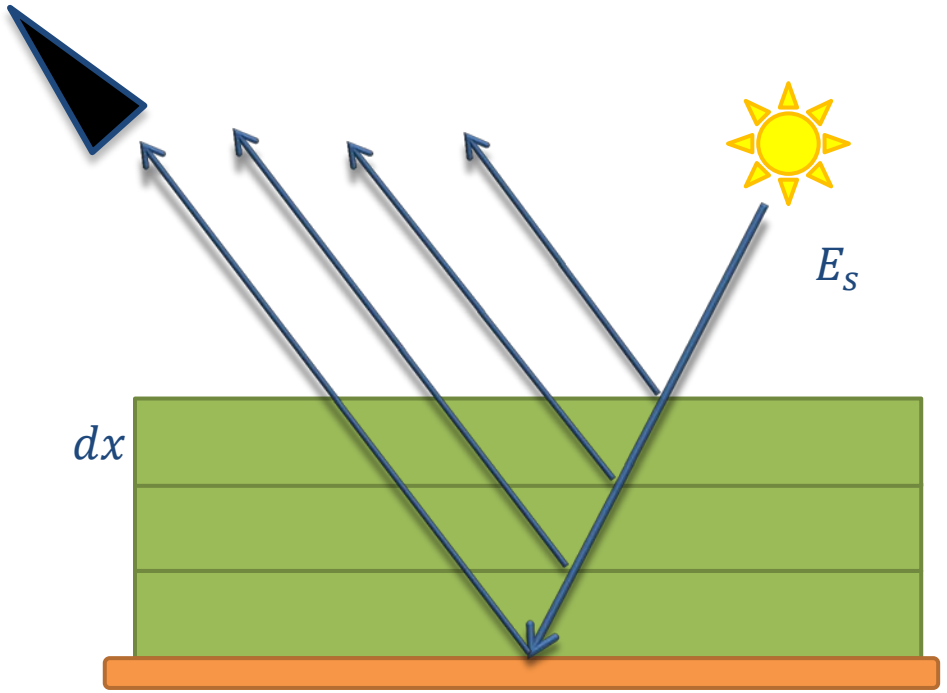
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Bidirectional scattering coefficient w

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

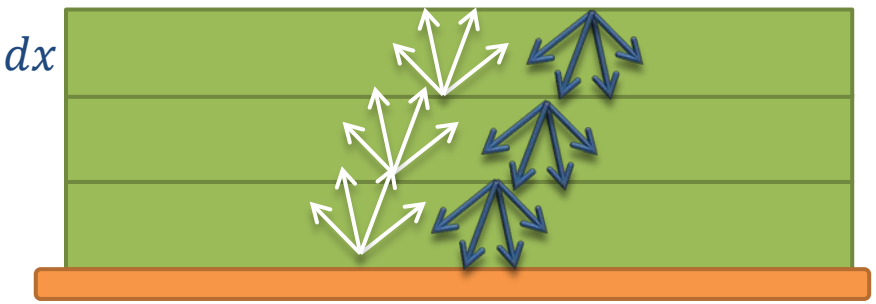
Backscatter coefficient σ

$$dE_s/dx = kE_s,$$

$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$

$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$

$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



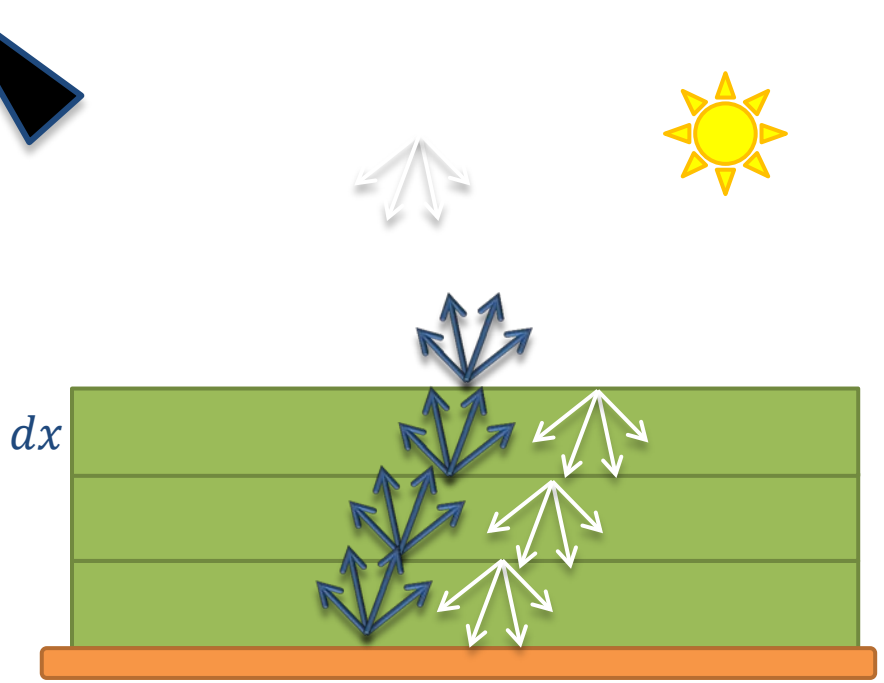
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Backscatter coefficient σ

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

E_s

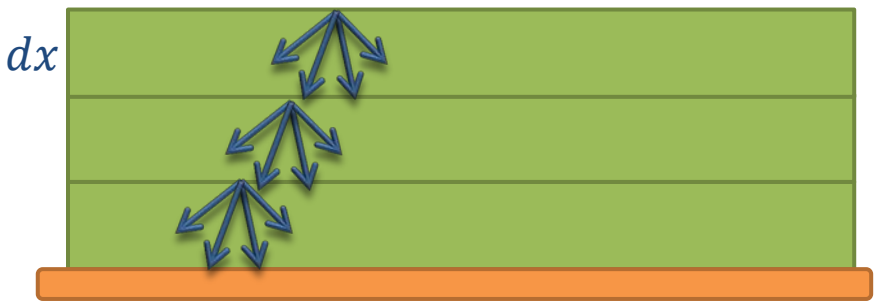
Attenuation $a = \kappa - \sigma'$

$$dE_s/dx = kE_s,$$

$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$

$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$

$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



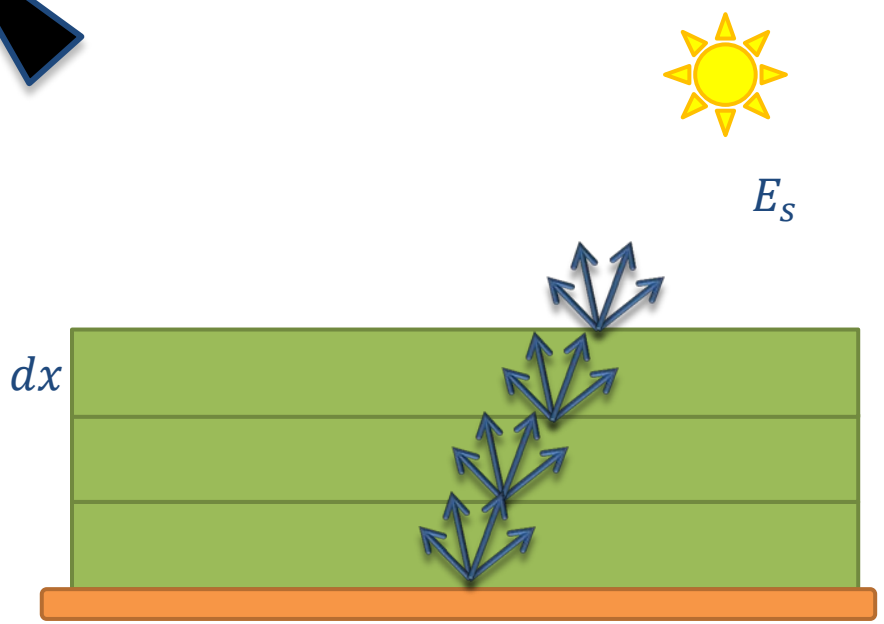
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Backscatter coefficient σ

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



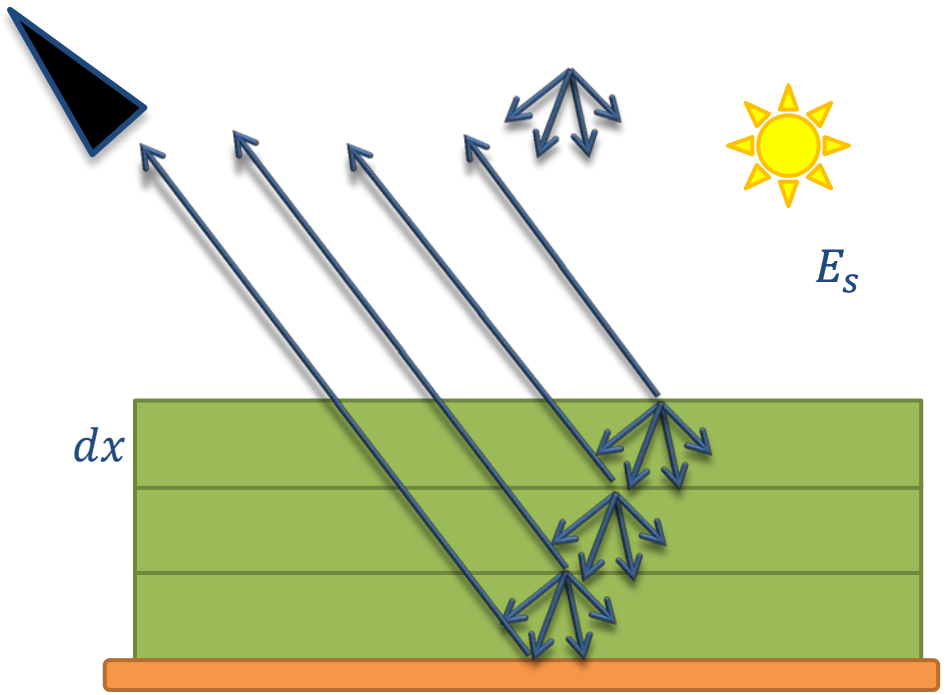
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Diffuse-directional scattering coefficient v

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



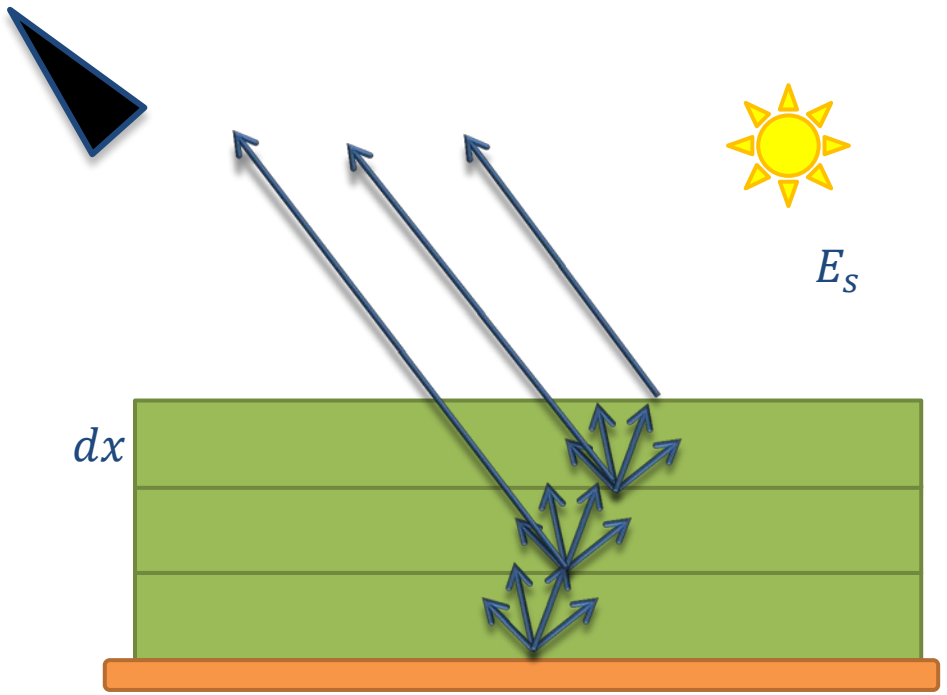
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Diffuse-directional scattering coefficient u

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



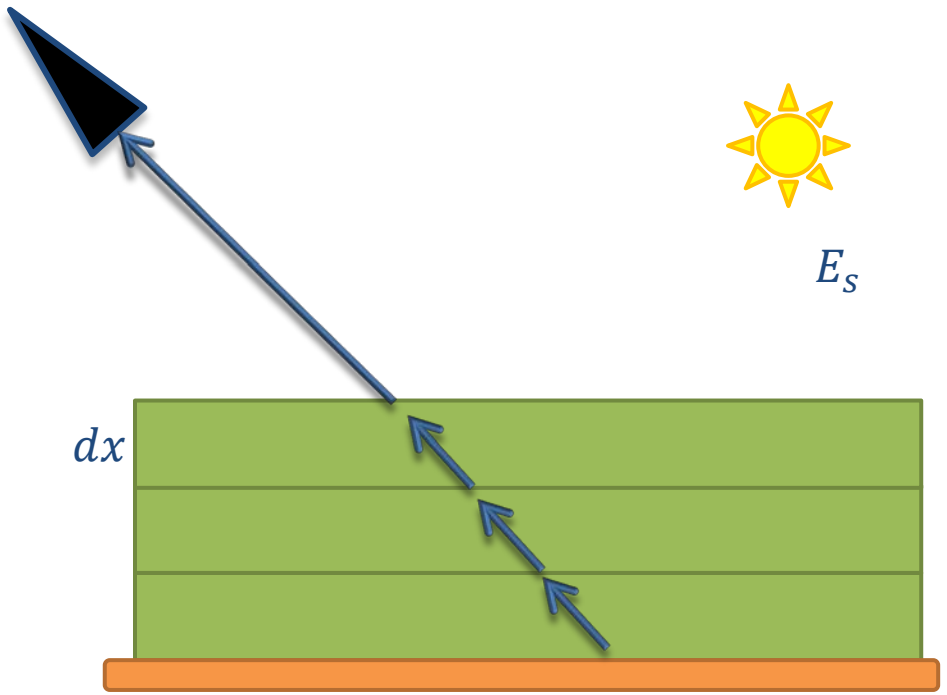
2. CANOPY RTM

- **SAIL** (Verhoef, 1984, 1985)
  - Scattering by Arbitrarily Inclined Leaves

System of 4 linear differential equations

Extinction coefficient K

$$dE_s/dx = kE_s,$$
$$dE_-/dx = -sE_s + aE_- - \sigma E_+$$
$$dE_+/dx = s'E_s + \sigma E_- - aE_+,$$
$$dE_o/dx = wE_s + vE_- + uE_+ - KE_o.$$



2. CANOPY RTM

- Extinction coefficients
  - Spectral invariants
  - Leaf-flux geometry
- Scattering coefficients
  - Geometrical component (f)
  - Leaf properties (ρ, τ)

Verhoef 1984

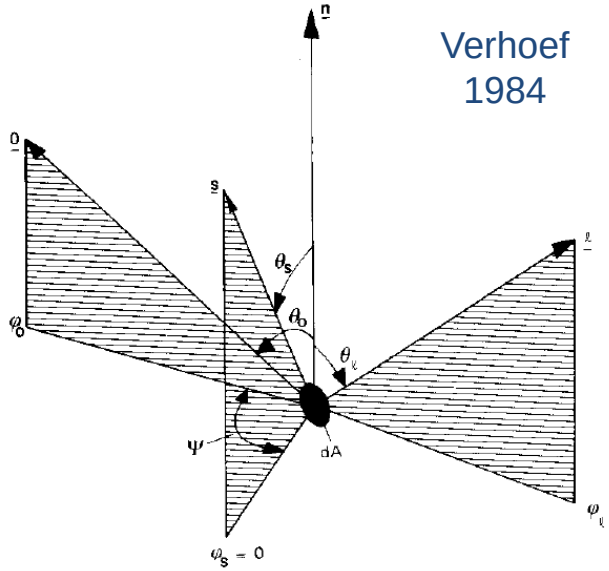


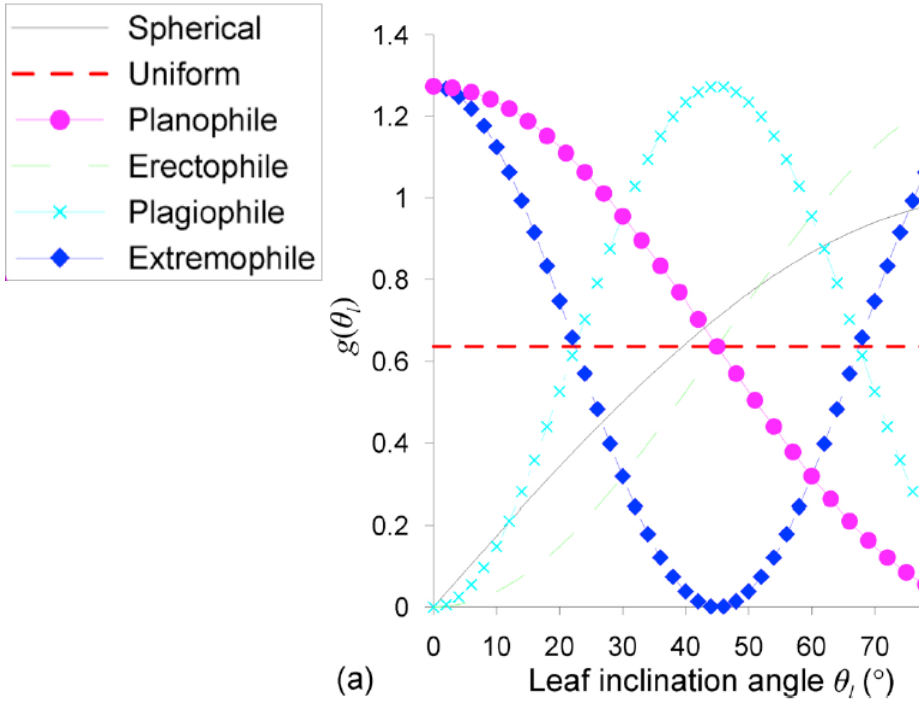
FIGURE 2. Orientations of unit vectors **l**, **n**, **s**, and **o** relative to a leaf area element dA.

Verhoef 1984

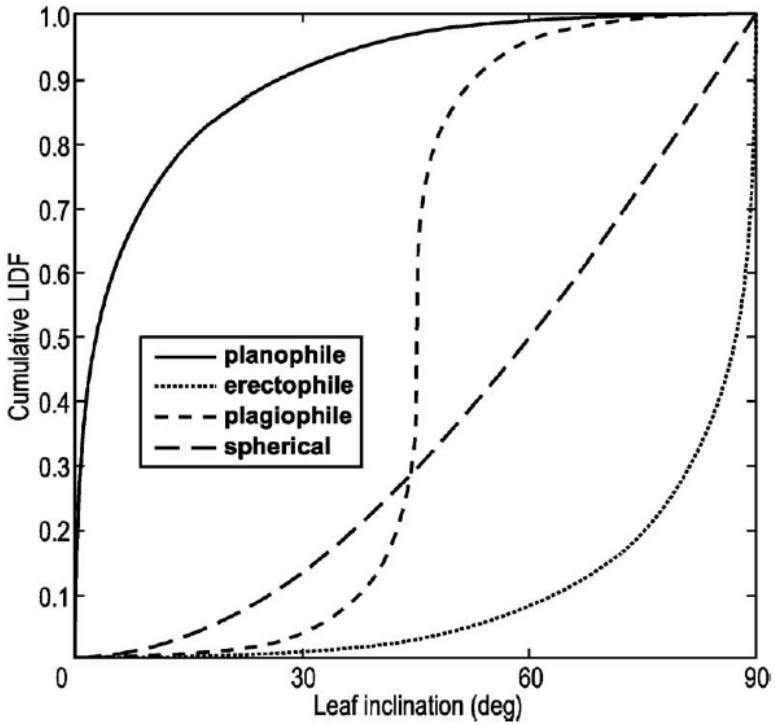
E_1 / E_2		E_s		E_-	E_+
		$f_s > 0$	$f_s < 0$		
E_o	$f_o > 0$	$f_s \rho f_o$	$-f_s \tau f_o$	$(\rho f_1 + \tau f_2) f_o$	$(\tau f_1 + \rho f_2) f_o$
	$f_o < 0$	$-f_s \tau f_o$	$f_s \rho f_o$	$-(\tau f_1 + \rho f_2) f_o$	$-(\rho f_1 + \tau f_2) f_o$
E_-		$f_s(\tau f_1 + \rho f_2)$	$-f_s(\rho f_1 + \tau f_2)$	$f_1(\tau f_1 + \rho f_2) + f_2(\rho f_1 + \tau f_2)$	$f_1(\rho f_1 + \tau f_2) + f_2(\tau f_1 + \rho f_2)$
E_+		$f_s(\rho f_1 + \tau f_2)$	$-f_s(\tau f_1 + \rho f_2)$	$f_1(\rho f_1 + \tau f_2) + f_2(\tau f_1 + \rho f_2)$	$f_1(\tau f_1 + \rho f_2) + f_2(\rho f_1 + \tau f_2)$

2. CANOPY RTM

- Leaf angle distribution function (LIDF)
  - Assume random azimuth angle distribution



Modified from Yan et al., 2019



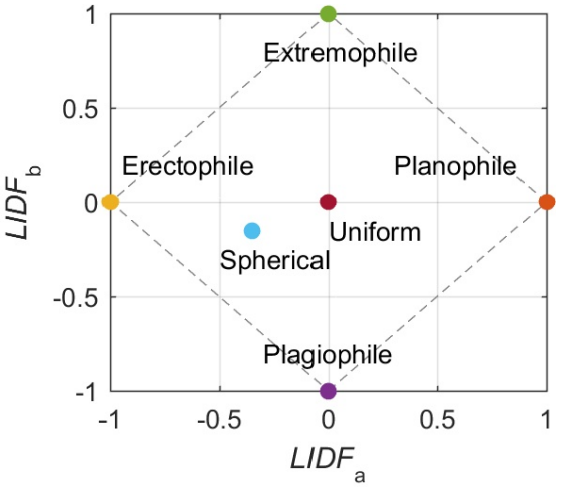
Verhoef et al., 2007

2. CANOPY RTM

- LIDF parameters
  - $LIDF_a$ ($\overline{\theta_\ell}$), $LIDF_b$ (shape)
  - $|a| + |b| < 1$

	LAD function $g(\theta_l)$	Average leaf inclination angle (θ)
Spherical	$g(\theta_l) = \sin \theta_l$	57.30
Uniform	$g(\theta_l) = 2 / \pi$	45.00
Planophile	$g(\theta_l) = 2\,(1 + \cos 2\theta_l) / \pi$	26.76
Erectophile	$g(\theta_l) = 2\,(1 - \cos 2\theta_l) / \pi$	63.24
Plagiophile	$g(\theta_l) = 2\,(1 - \cos 4\theta_l) / \pi$	45.00
Extremophile	$g(\theta_l) = 2\,(1 + \cos 4\theta_l) / \pi$	45.00

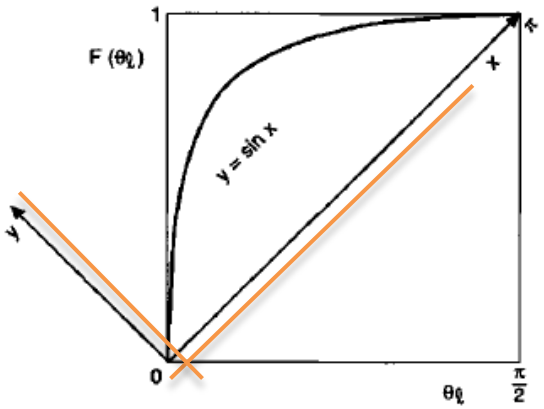
Yan et al., 2019



- $F(\theta_\ell) = \dfrac{2\left(a \sin x + \frac{1}{2} b \cos 2x + \theta_\ell\right)}{\pi}$
  - Iteration

$x = 2\theta_\ell$
Repeat
$y = a \sin x + \frac{1}{2} b \sin 2x$
$\Delta x = \frac{1}{2}(y - x + 2\theta_\ell)$
$x = x + \Delta x$
Until $|\Delta x| < t$
$F(\theta_\ell) = 2(y + \theta_\ell)/\pi$

Verhoef, thesis, 1998



$x = \frac{\pi}{2} F(\theta_\ell) + \theta_\ell$
$y = \frac{\pi}{2} F(\theta_\ell) - \theta_\ell$

Graphical method and coordinate transformation. Verhoef, thesis., 1998

2. CANOPY RTM

- SAIL model parameters
  - Leaf Area Index (LAI or L)
    - "*total one-sided leaf area per unit layer area*" (Verhoef, 1984)
- All fluxes per leaf area: $L \cdot dx$

  - Hot spot parameter (s_ℓ)
    - $\theta_{\text{view}} = \theta_{\text{sun}}$ and $\varphi_{\text{view}} = \varphi_{\text{sun}}$
    - s_ℓ: "ratio of the correlation length of leaf projections in the horizontal plane and the canopy height"

$$q = \frac{\alpha}{s_\ell} \frac{2}{K+k}$$

$$P_{\text{so}}(x) = \exp\left[(K+k)Lx + \sqrt{Kk}L(1-e^{qx})/q\right]$$

Verhoef et al., 2007

2. CANOPY RTM

- SAIL: Analytical solution

$$\frac{d}{dx}(\mathbf{E}) = M\mathbf{E}, \xrightarrow{\text{Linear transformation } Y} \frac{d}{dx}(\mathbf{F}) = \Lambda\mathbf{F}, \quad \text{with } \Lambda = YMY^{-1},$$

$\mathrm{F} \rightarrow$ transformed fluxes

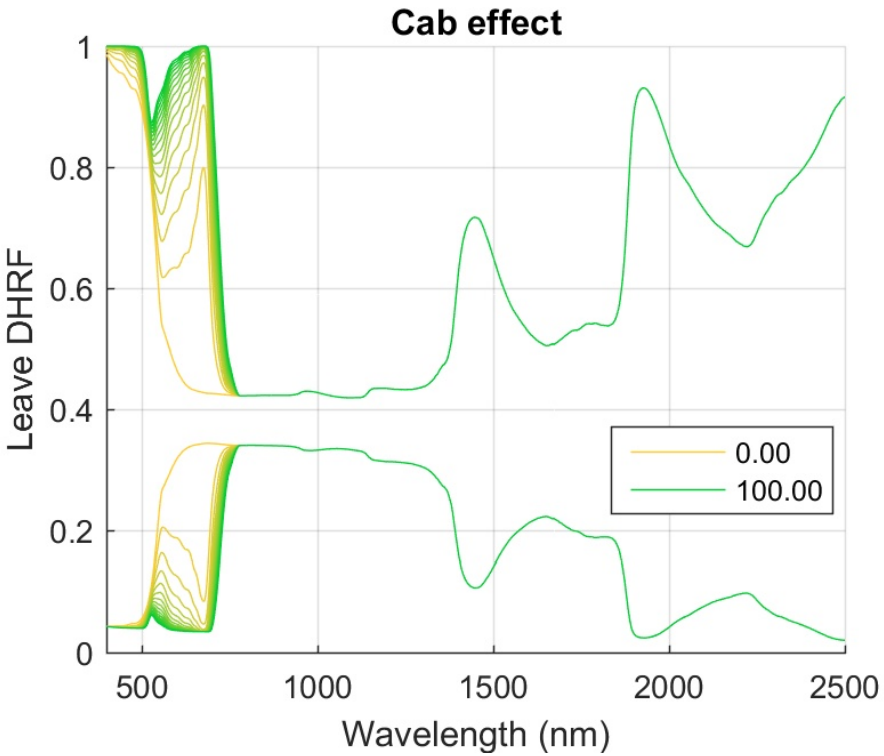
$\Lambda \rightarrow$ eigenvalues of M; $[k, m{=}\sqrt{a^2 - \sigma^2}, K]$

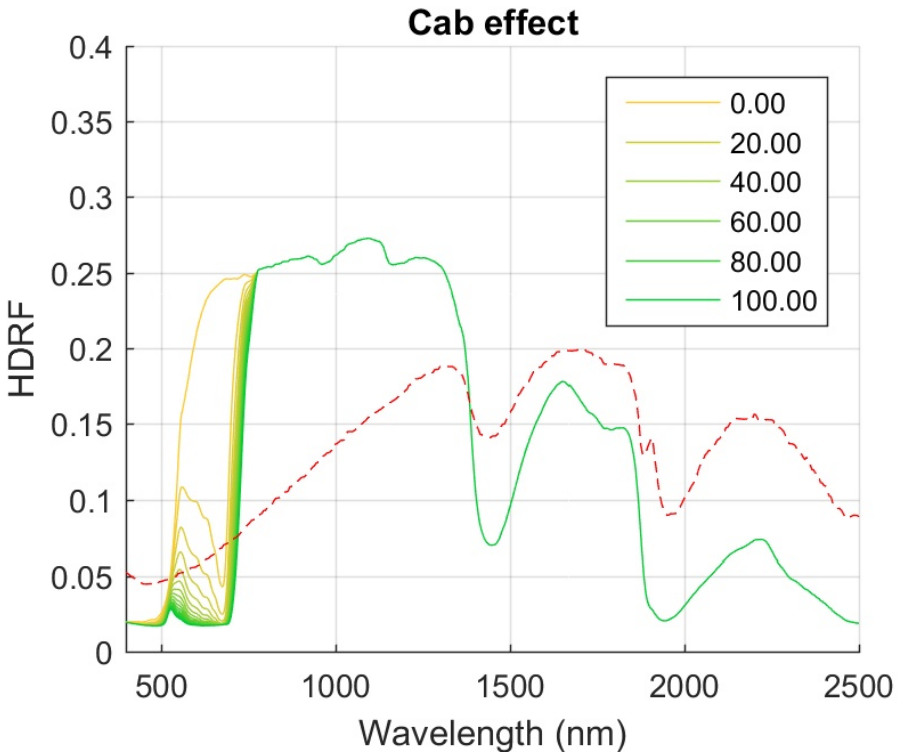
All the these models rely on discrete leaf inclination and azimuth angles

- Other models: Numerical solution
  - SCOPE (van der Tol et al. 2009), mSCOPE (Yang et al. 2009)
  - Discretized layers

2. CANOPY RTM

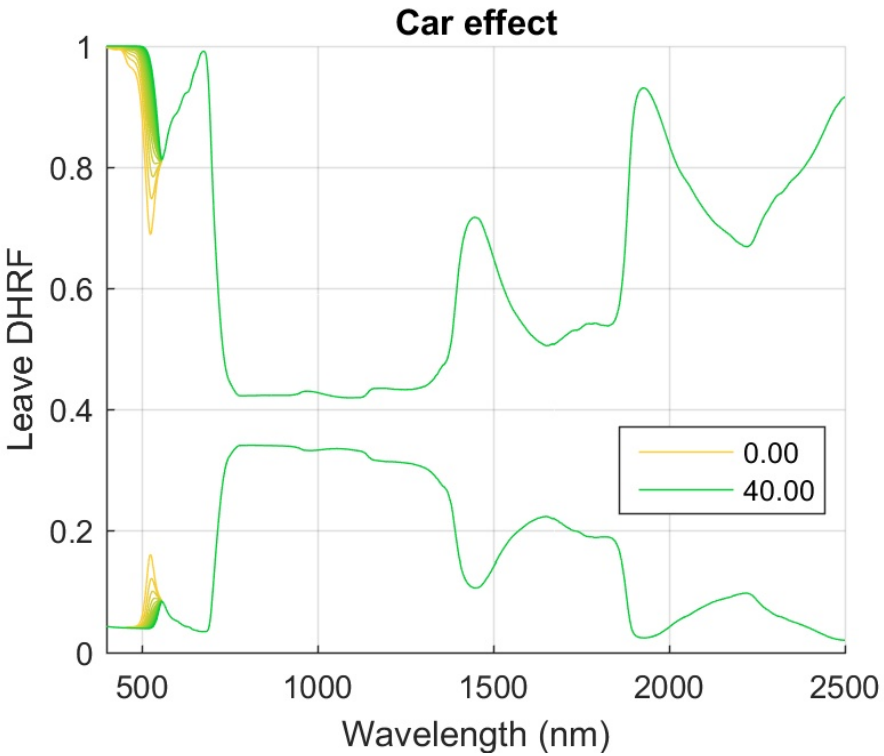
- From leaf to canopy. Chlorophyll a + b

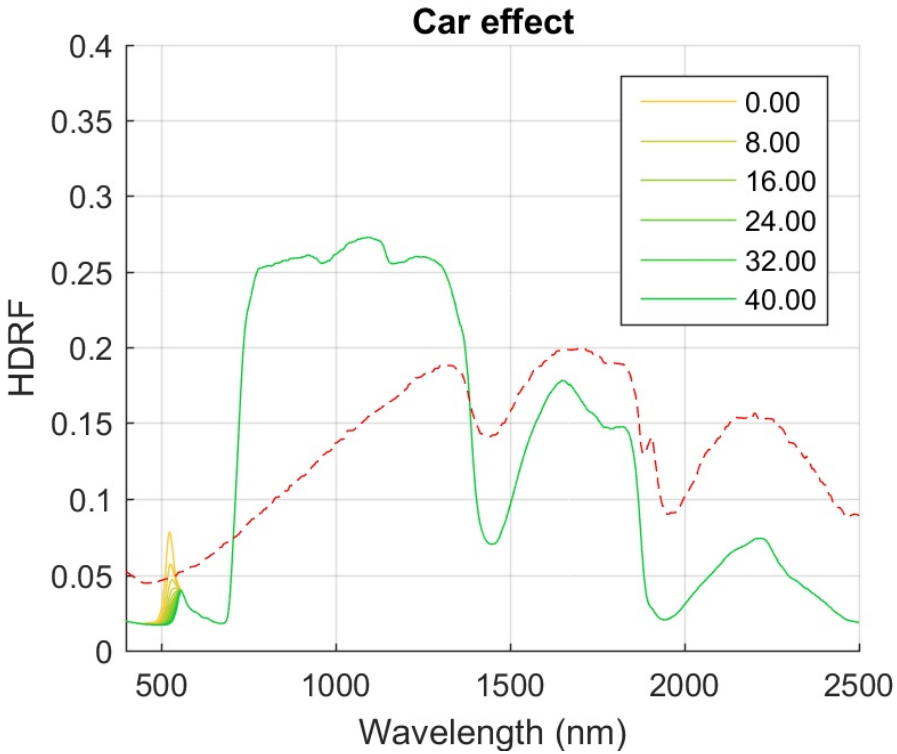




2. CANOPY RTM

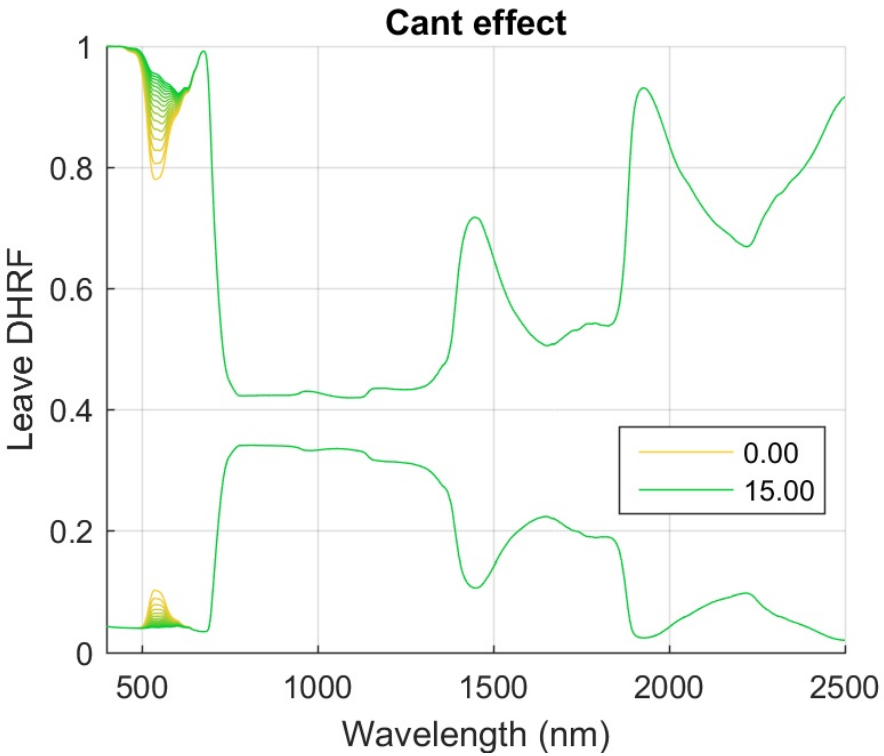
- From leaf to canopy. Carotenoids

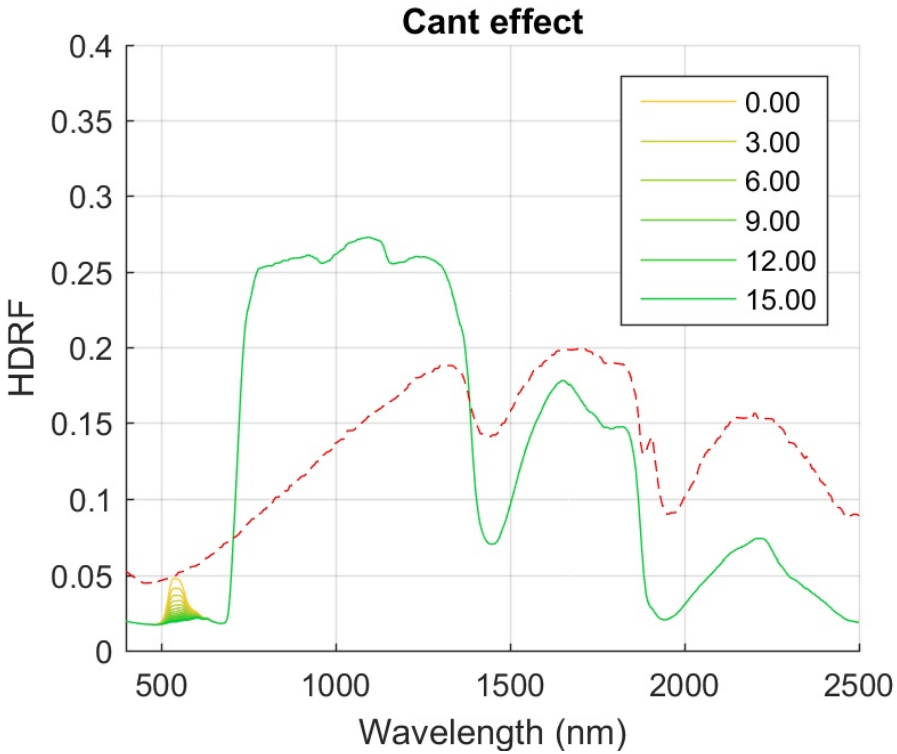




2. CANOPY RTM

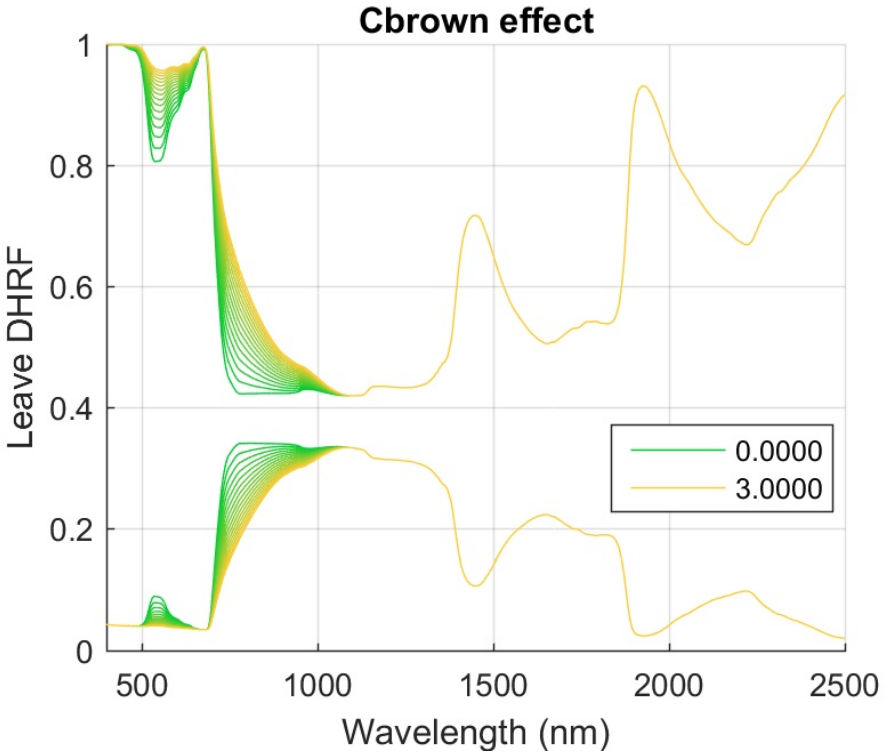
- From leaf to canopy. Anthocyanins

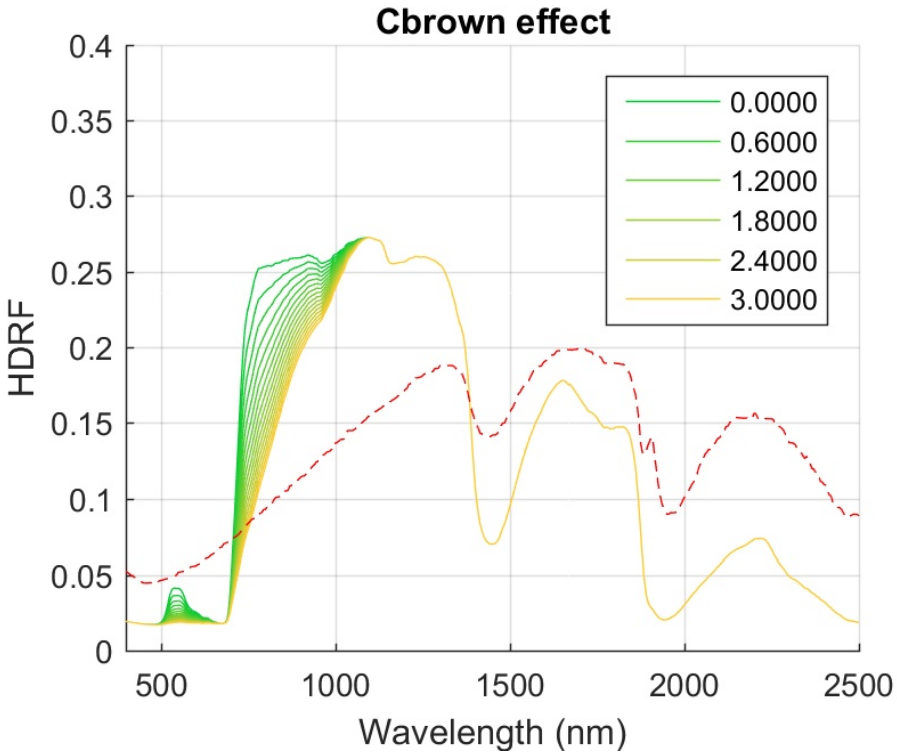




2. CANOPY RTM

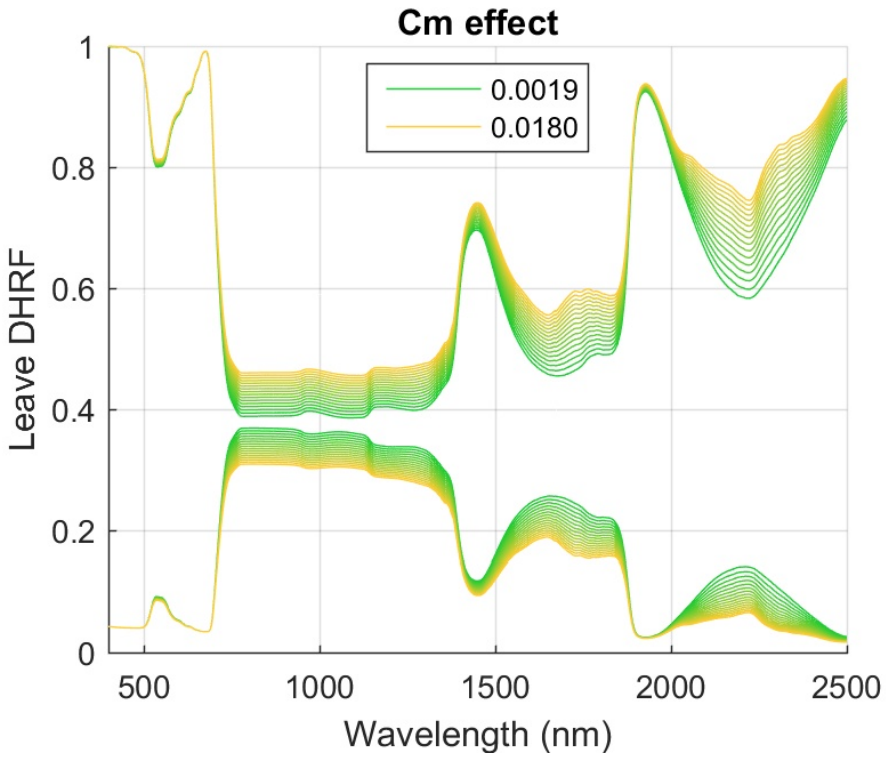
- Brown/senescent pigments

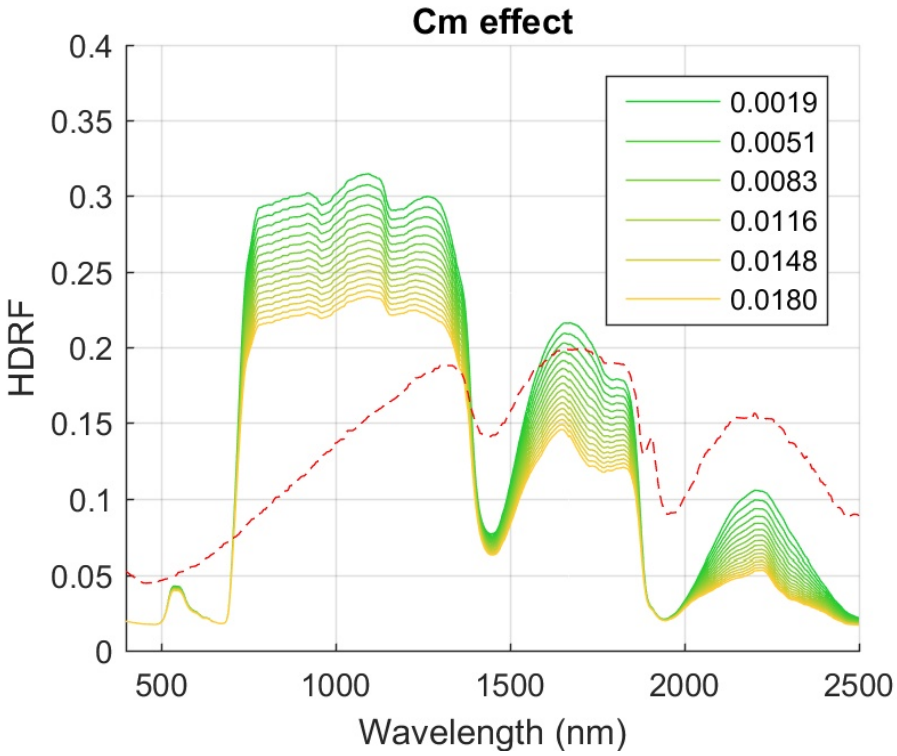




2. CANOPY RTM

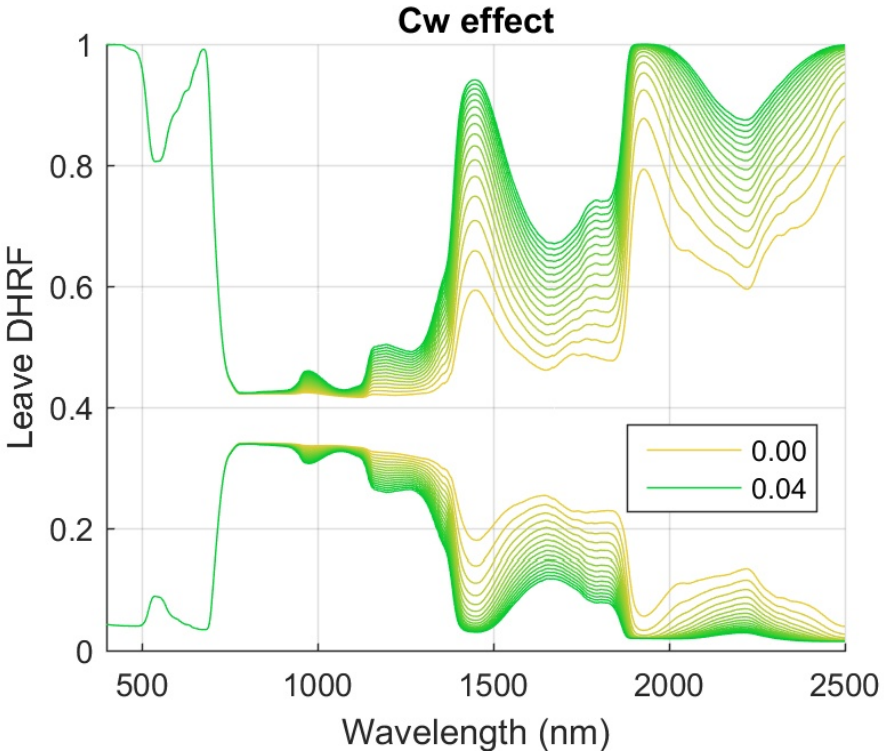
- From leaf to canopy. Dry matter

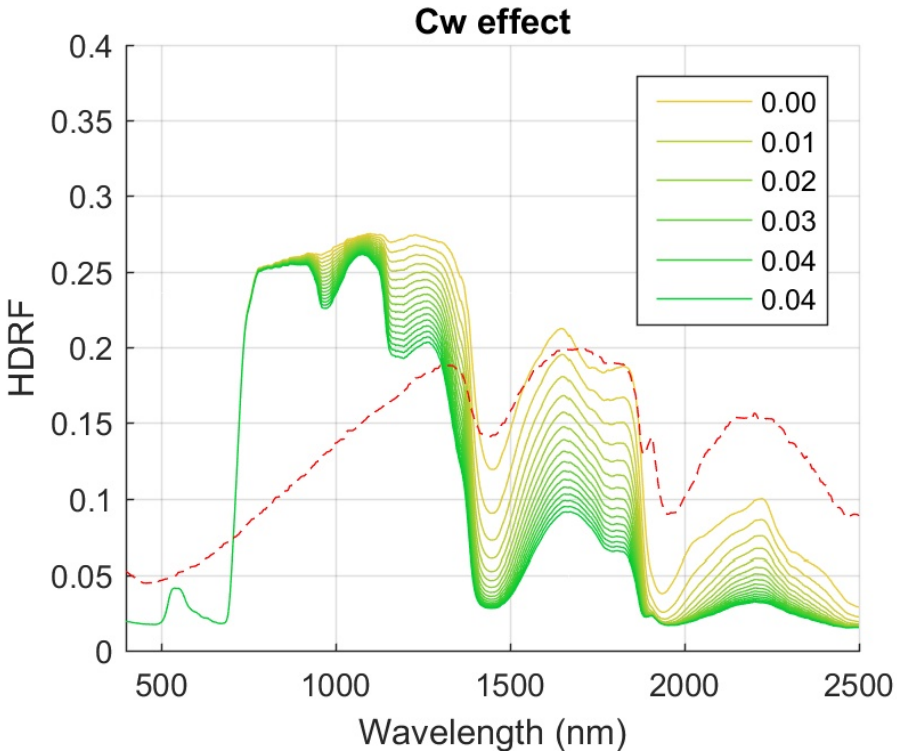




2. CANOPY RTM

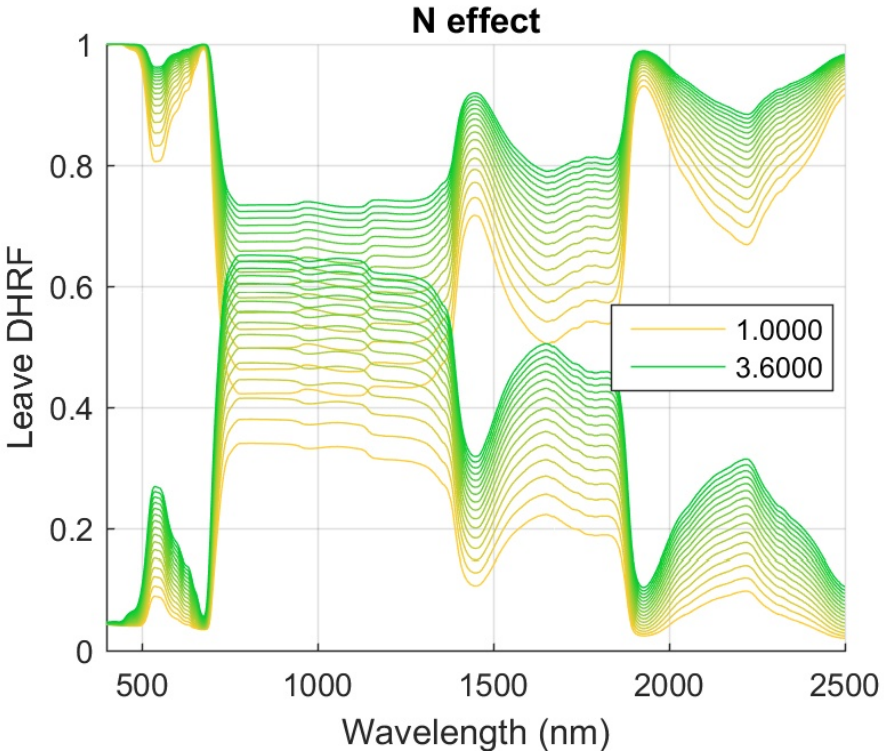
- From leaf to canopy. Water

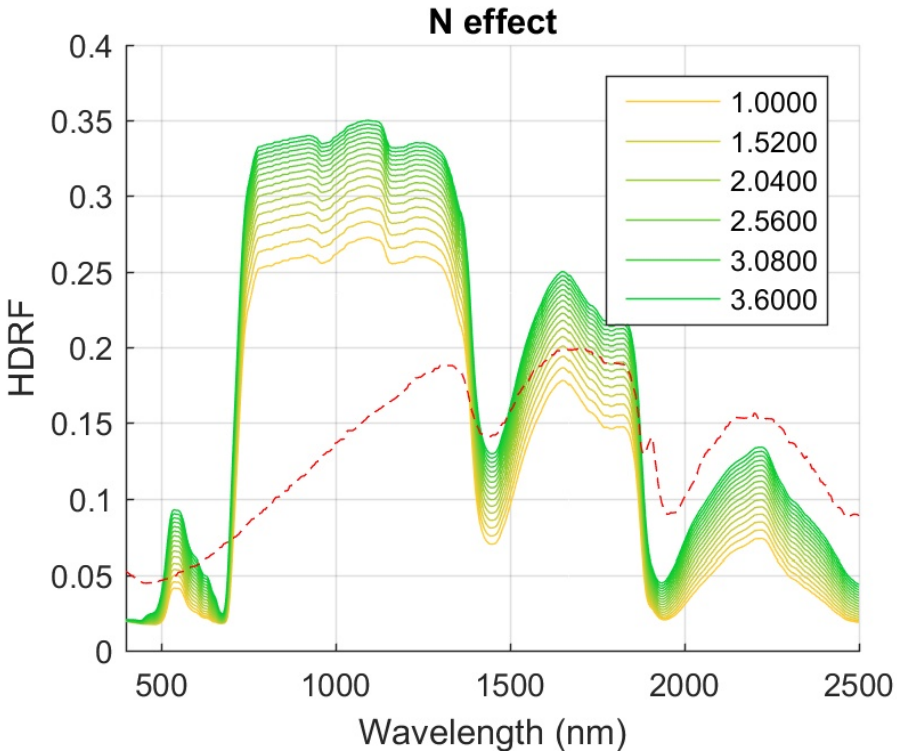




2. CANOPY RTM

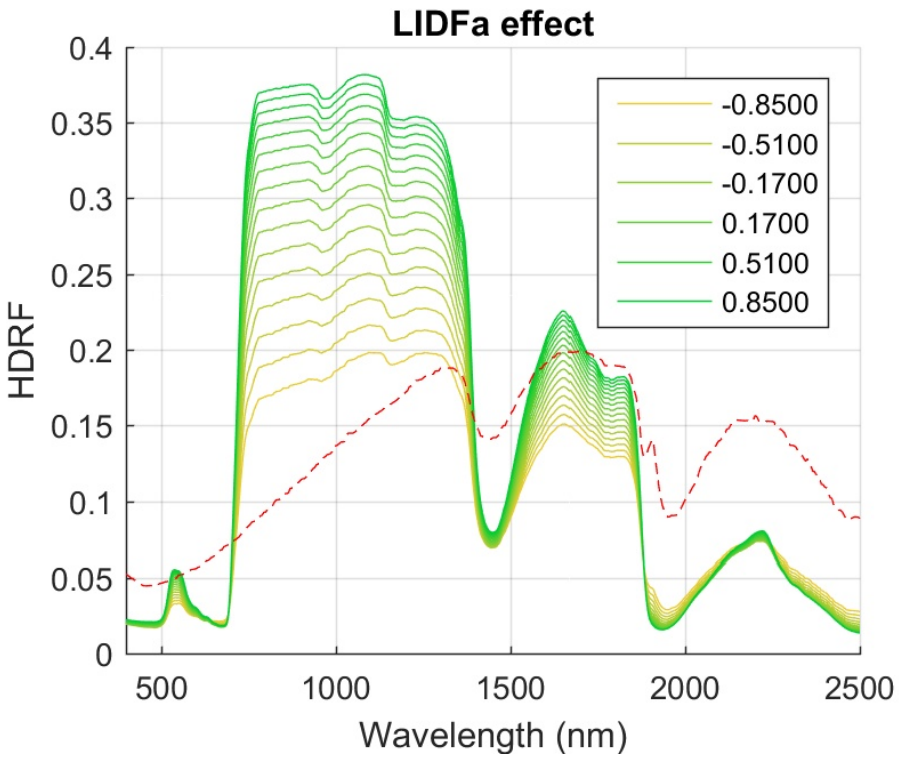
- From leaf to canopy. N

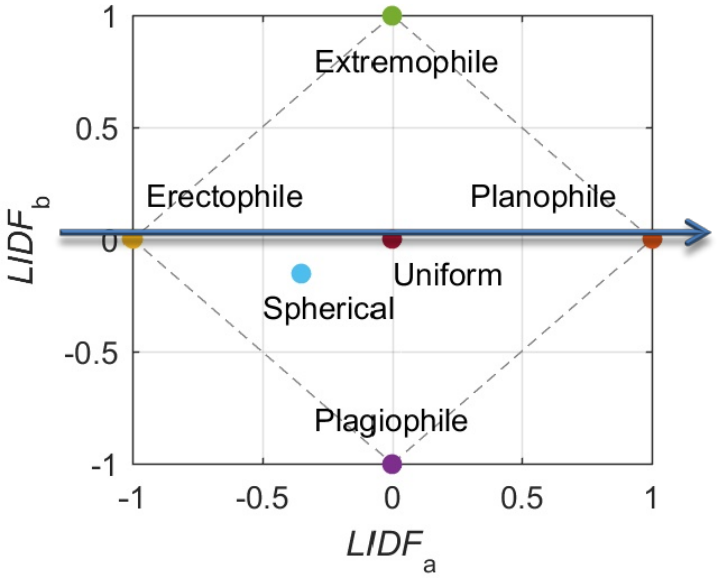




2. CANOPY RTM

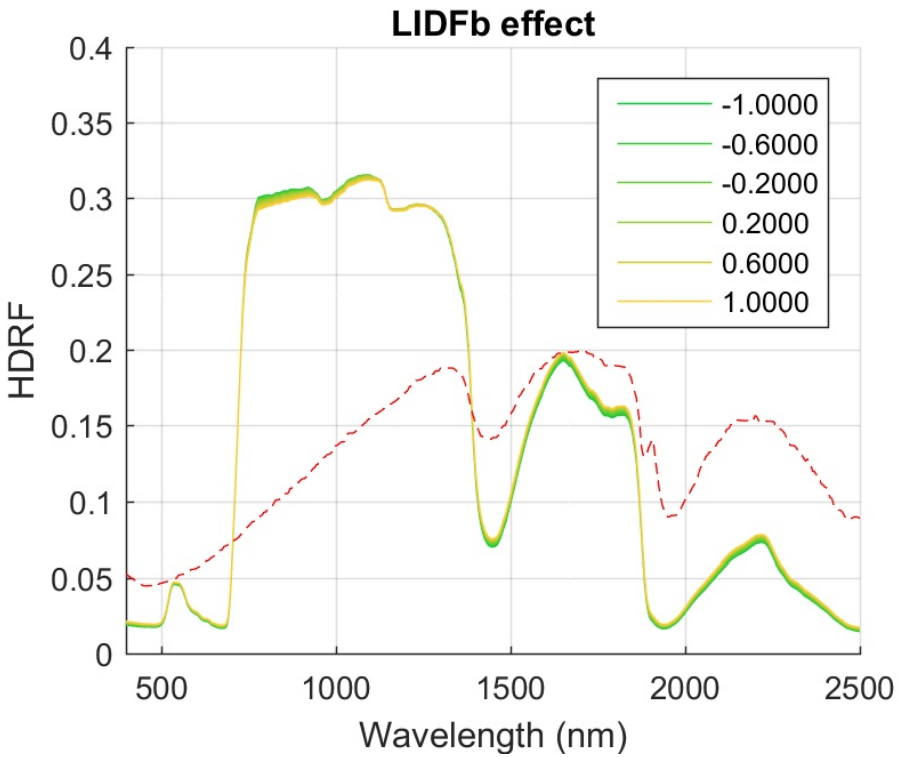
- $LIDF_a$

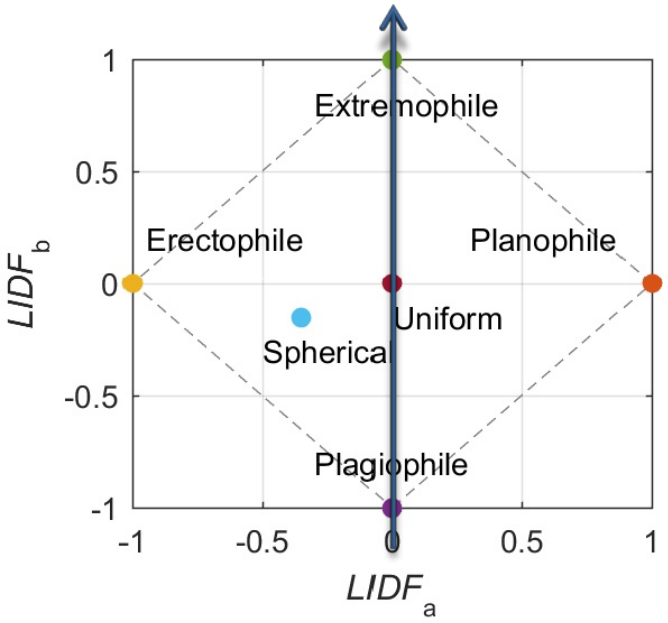




2. CANOPY RTM

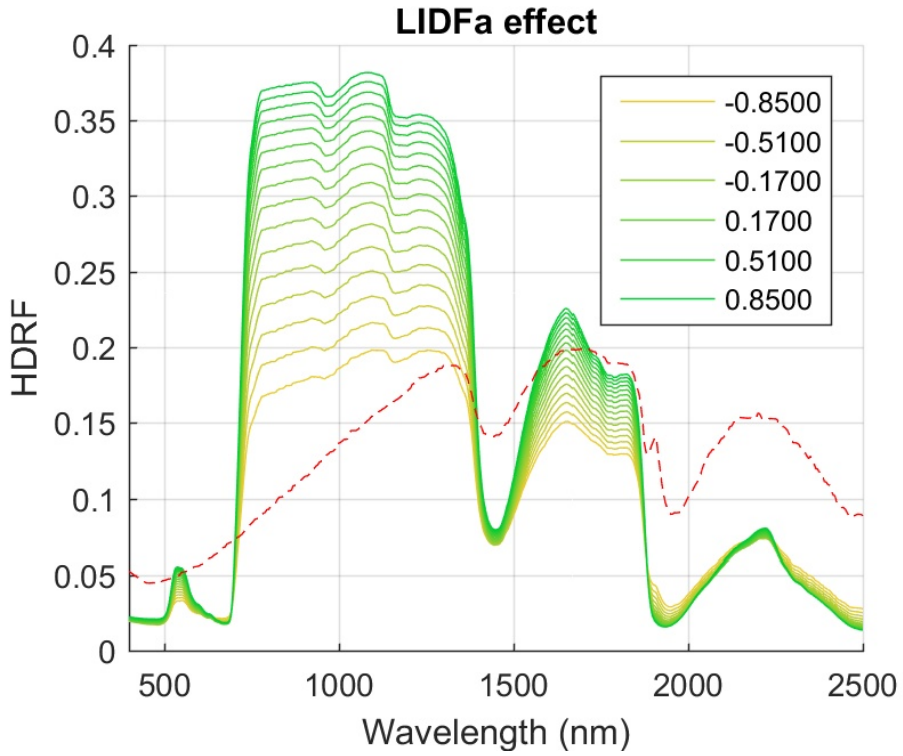
- $LIDF_b$





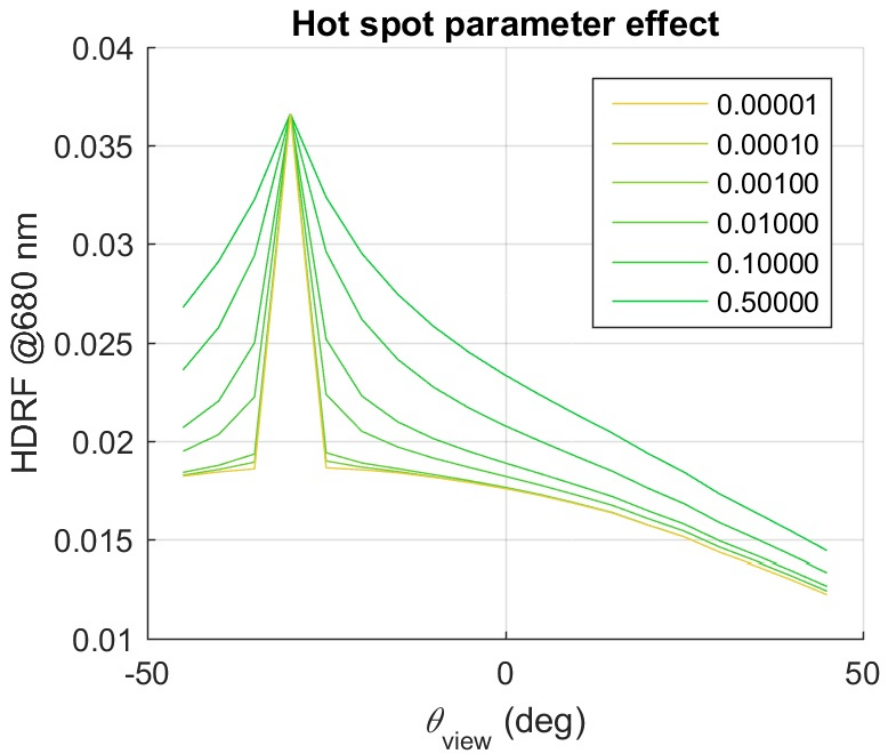
2. CANOPY RTM

- Leaf Area Index



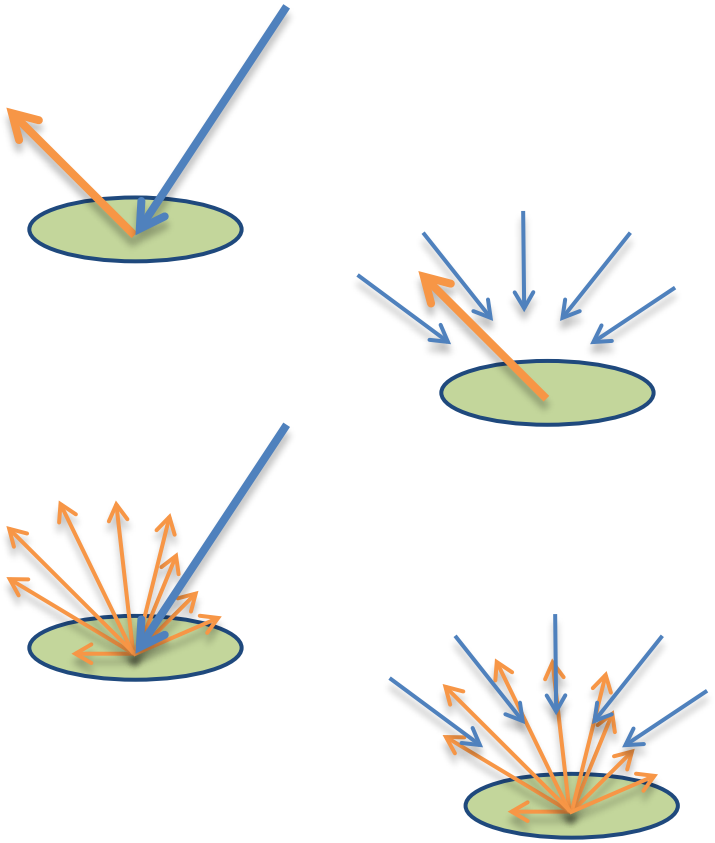
2. CANOPY RTM

- Hot spot parameter



3. REFLECTANCE FACTORS

- Direct and diffuse reflected light
  - PROSAIL
    - r_{so}: bi-directional
    - r_{do}: hemispherical-directional
    - r_{sd}: directional-hemispherical
    - r_{dd}: bi-hemispherical



3. REFLECTANCE FACTORS

- Direct and diffuse reflected light
  - Proximal sensing case
    - Bottom of the atmosphere
    - Observed reflectance factor
      - $r_{\mathrm{obs}} = \frac{\pi L_{\mathrm{o}}}{E_{\mathrm{tot}}}$;
    - Reflected light
      - $r = \frac{(r_{\mathrm{so}} E_{\mathrm{sun}}) + (r_{\mathrm{do}} E_{\mathrm{sky}})}{E_{\mathrm{tot}}} = (1 - \delta) r_{\mathrm{so}} + \delta r_{\mathrm{do}}$

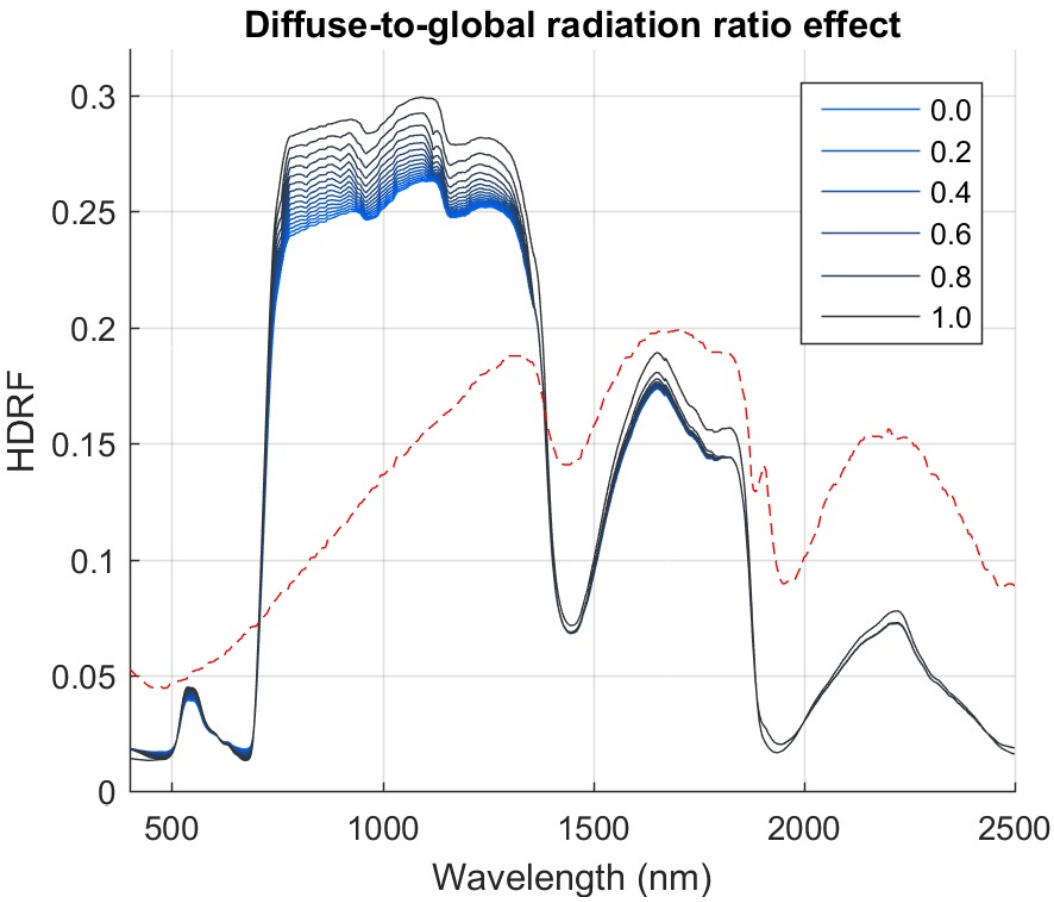
      where $\delta(\lambda) = \frac{E_{\mathrm{sky}}(\lambda)}{E_{\mathrm{tot}}(\lambda)}$; diffuse-to-global radiation ratio

3. REFLECTANCE FACTORS

- Direct and diffuse reflected light
  - Simulation

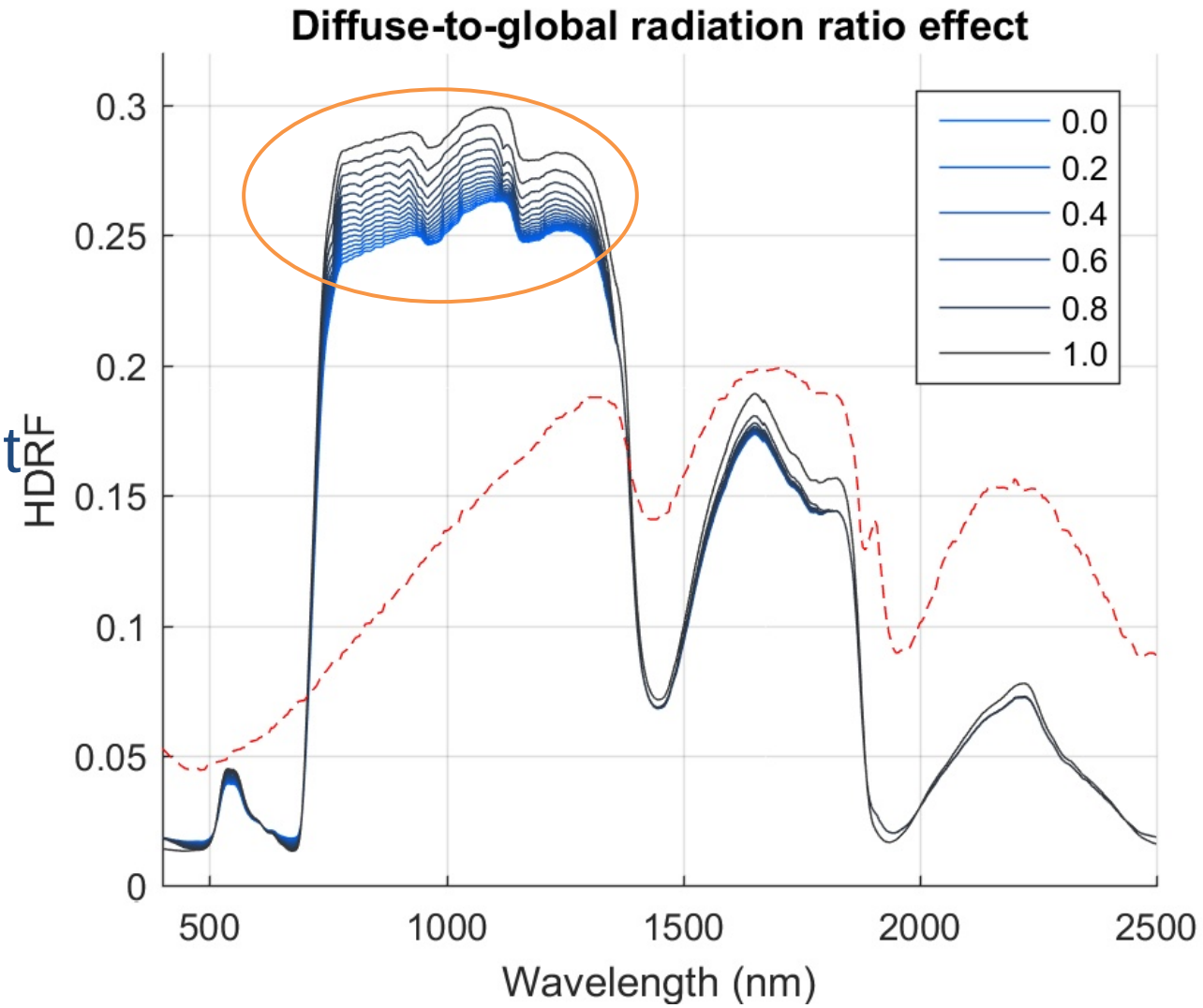
$$r = \frac{(r_{so} E_{sun}) + (r_{do} E_{sky})}{E_{tot}}$$

    - Canopy RTM predicts r_{so} and r_{do}
    - What about E_{sun} and E_{sky}?



3. REFLECTANCE FACTORS

- Direct and diffuse reflected light
  - Diffuse light shows more interception with the canopy



3. REFLECTANCE FACTORS

- Direct and diffuse reflected light
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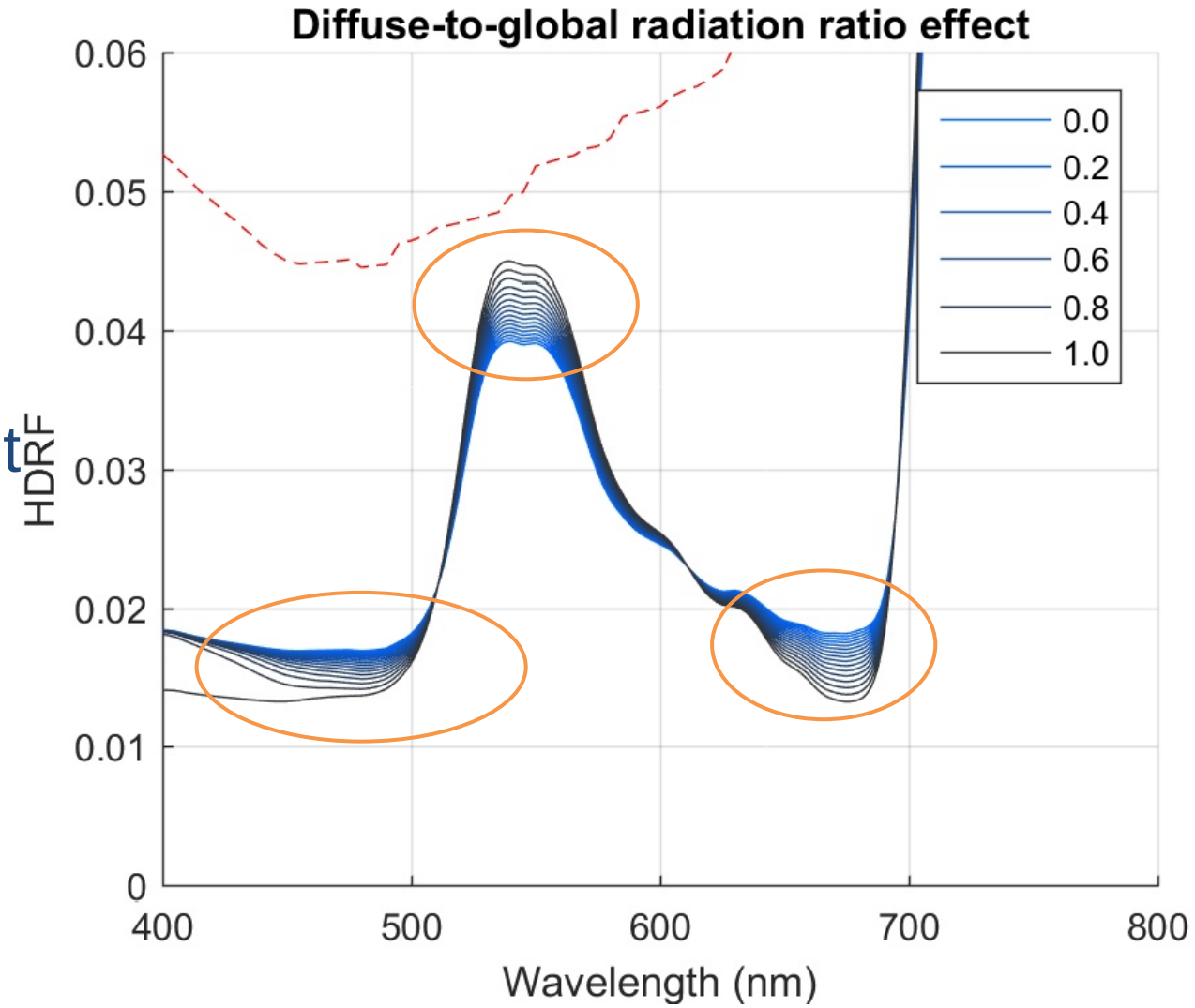
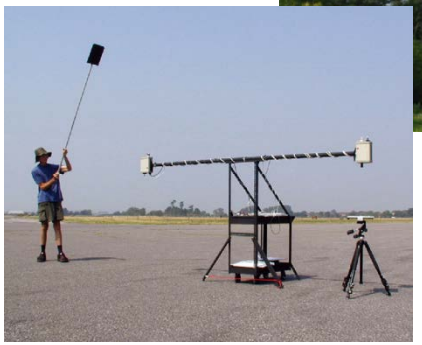


3. REFLECTANCE FACTORS

- Light characterization
  - Measurement
    - Shading disc + integrating sphere
    - ~ Shading calibrated Spectralon® panel
    - Delta-T SPN1

www.delta-t.co.uk

Milton et al., 2009



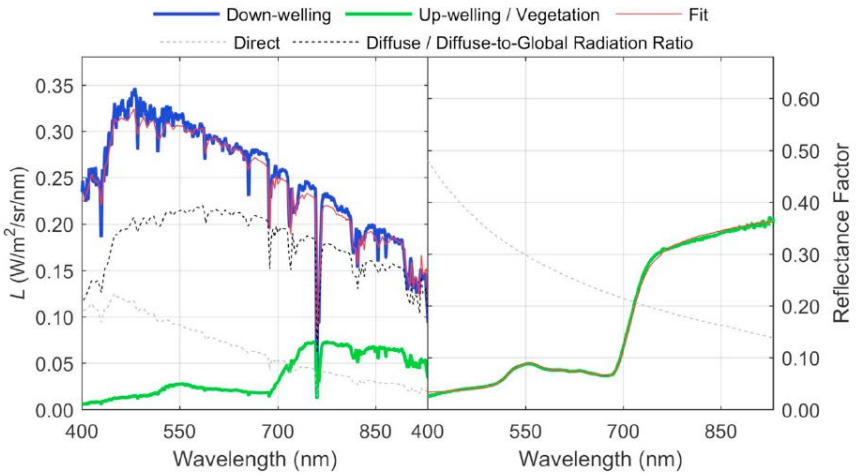
Kuusk and Kuusk 2018

  - Simulated
    - Measure atmospheric parameters
      - Microtops II Sunphotometer
      - Cimel CE 318-2 (automatic)
    - Forward atmospheric RTM

https://fsf.nerc.ac.uk/instruments/Sunphos.shtml

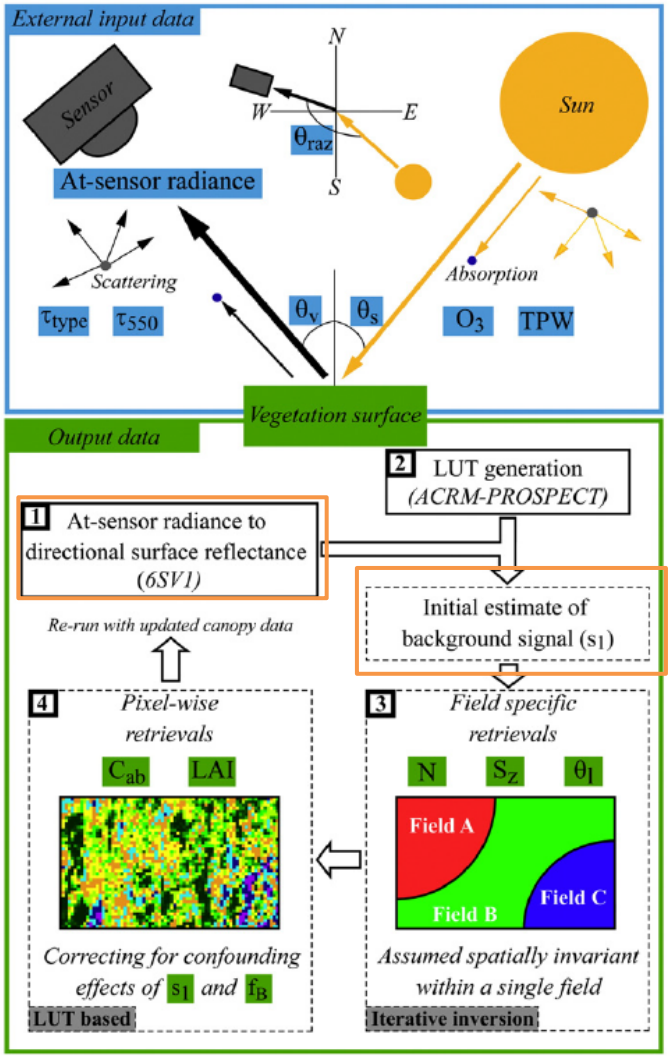
3. REFLECTANCE FACTORS

- Estimated (RTM inversion)
  - Atmospheric RTM inversion



Pacheco-Labrador et al., 2019

- Coupled Atmospheric-Vegetation RTM inversion
  - Remote sensors



Houborg, R., & Anderson, M. (2009)

THANKS!