PROSPECT+SAIL: 15 Years of Use for Land Surface Characterization

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Physiological processes at different scales like photosynthesis, evapotranspiration, carbon storage, decomposition of organic matter, etc. partly depend on:

- plant species and age, canopy density and architecture, etc.
- leaf anatomy
- leaf biochemical composition, i.e. photosynthetic pigments, water, carbon, nitrogen, etc.

Why are we interested in plant canopies?

Vegetation provides foundations for life on Earth through ecological functions: regulation of climate and water resources, habitat for animals, supply of food and goods.
Plant canopy reflectance depends on:

- measurement configuration
- soil reflectance
- leaf reflectance and transmittance
- plant architecture
  → Leaf Area Index
  → Leaf Inclination Distribution Function
  → leaf size / canopy height
  → cover fraction
  → etc.
- illumination conditions: diffuse / direct
Spectral or directional reflectance measurements?


Information content

multi-angular measurements

1 wavelength, n viewing angles
information on plant architecture

\[ \rho\left(\lambda, \theta_s, \varphi_s, \theta_v^{(1)}, \varphi_v^{(1)}\right) \]
\[ \rho\left(\lambda, \theta_s, \varphi_s, \theta_v^{(2)}, \varphi_v^{(2)}\right) \]
\[ \cdots \]
\[ \rho\left(\lambda, \theta_s, \varphi_s, \theta_v^{(n)}, \varphi_v^{(n)}\right) \]

multi-spectral measurements

n wavelengths, 1 viewing angle
information on plant biochemistry

\[ \rho\left(\lambda^{(1)}, \theta_s, \varphi_s, \theta_v, \varphi_v\right) \]
\[ \rho\left(\lambda^{(2)}, \theta_s, \varphi_s, \theta_v, \varphi_v\right) \]
\[ \cdots \]
\[ \rho\left(\lambda^{(n)}, \theta_s, \varphi_s, \theta_v, \varphi_v\right) \]
Understanding the RT at different scales

- **At the canopy level**: 5 m
- **At the leaf level**: 150 µm
- **At the soil level**: 70 km
- **At the satellite level**: 50 cm
Coupling of RT models

- Anatomy
  - Chlorophyll
  - Dry matter
  - Water

- LAI
  - Leaf orientation
  - Hot spot parameter
  - Cover fraction

- Albedo
  - Phase function
  - Roughness

- θ
  - θ₀
  - θᵥ
  - ϕᵥ

- PROSPECT
  - \( \rho_l(\lambda) \)
  - \( \tau_1(\lambda) \)

- SAIL
  - \( \rho_s(\lambda, \theta_s, \theta_v, \varphi_v) \)

- HAPKE

- 6S
  - \( \rho^*(\lambda, \theta_s, \theta_v, \varphi_v) \)
  - \( \rho_c(\lambda, \theta_s, \theta_v, \varphi_v) \)

Direct mode
Inverse mode
Light Scattering by Leaf Layers with Application to Canopy Reflectance Modeling: The SAIL Model

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PROSPECT: A Model of Leaf Optical Properties Spectra

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How PROSPECT+SAIL were used in direct mode?

- To study the spectral shifts (red-edge) and deformations as a function of the canopy input variables one-by-one.

- To design or test vegetation indexes:
  - Weighted Difference Vegetation Index $\rightarrow$ LAI
  - Transformed Chlorophyll Absorption in Reflectance Index $\rightarrow$ $C_{ab}$
  - Simple Ratio Water Index $\rightarrow$ $C_w$

- To perform sensitivity analyses intended to quantify the contribution of the canopy input variables: selection of optimized spectral bands (number, position, width) and viewing directions (number, position) for new sensors.
Simulations with PROSPECT+SAIL

Solar zenith angle: $\theta_s = 20^\circ$
Viewing zenith angle: $\theta_v = 0^\circ$
Leaf orientation: spherical
Horizontal visibility: VIS = 100 km

Leaf structure parameter: N = 1.5
Total chlorophyll content: $C_{ab} = 50 \, \mu g \, cm^{-2}$
Water content: $C_w = 0.01 \, cm$
Dry matter content: $C_m = 0.005 \, g \, cm^{-2}$
Spectral sensitivity analysis of PROSPECT+SAIL

Design Of Experiments for Simulation

Directional sensitivity analysis of PROSPECT+SAIL


Chlorophyll content
Leaf Area Index
Mean leaf inclination angle
Chlorophyll content (µg cm$^{-2}$)  Leaf Mass per Area (g m$^{-2}$)

Water content (mg H$_2$O / g dry weight)

Santa Monica Mtns: Canopy Water Content

Sept. 19, 1994

May 9, 1995

How to use PROSPECT+SAIL in inverse mode?

Iterative algorithms, look-up-tables

calibrated data

Minimum distance criterion

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

Artificial neural networks

Input layer | Hidden layer | Output layer
---|---|---
\( \rho(\lambda_1) \) | | Canopy variable 1
\( \rho(\lambda_2) \) | | Canopy variable 2
\( \rho(\lambda_n) \)
PROSPECT+SAILH inversion performed using iterative methods

**Ex** Airborne POLDER image (ReSeDA 1997 field experiment)  
4 wavebands in the VIS-NIR + about 50 viewing angles

*Chlorophyll content (µg cm⁻²)*

PROSPECT+GeoSAIL inversion performed using look-up-tables

**Ex** Landsat image (13 August 2002)
3 wavebands in the VIS-NIR + 1 viewing angle

**Leaf Area Index**

- range 0 - 8

**Vegetation cover**

- range 50 - 100%

PROSPECT+SAILH inversion performed using artificial neural networks

Ex Airborne POLDER image (ReSeDA 1997 field experiment)
4 wavebands in the VIS-NIR + about 50 viewing angles

Gap fraction
Leaf Area Index

**Conclusion**

- PROSPECT+SAIL is now a widely used RT code which has been validated on various natural or agricultural vegetation canopies over the years.

- It is simple, fast, accurate, and accessible to the scientific community.

- It links the canopy variables describing the plant biochemistry to the ones describing their architecture and it allows to reduce the dimensionality of the inverse problem when using multispectral or hyperspectral data.

- It is still evolving: the introduction of new leaf pigments, of leaf specular reflectance, of solar induced chlorophyll fluorescence, the consideration of plant heterogeneities (crown clumping effect) will open up new vistas in the monitoring of terrestrial ecosystems.
Latest development: FluoSAIL

PS2 @ 690 nm and PS1 @ 730 nm


Latest development: 4SAIL

Thank you for your attention
Variability of plant canopy reflectance