# Introduction of PROSAIL

PROSAIL is the combination of PROSPECT (a leaf optical property model) and SAIL (a canopy bidirectional reflectance model). It links the spectral variation of canopy reflectance (mainly related to leaf biochemical contents) with its directional variation (primarily related to canopy architecture and soil/vegetation contrast) which is key to simultaneous estimation of canopy biophysical/structural variables for applications in agriculture, plant physiology, or ecology, at different scale (Jacquemoud et al., 2009).

PROSAIL is a popular radiative transfer model (RTM) which is based on physical laws and describes how radiation interacts with vegetation canopies. Inversion of RTMs is commonly used to estimate vegetation bio-physical/-chemical parameters (i.e. leaf area index) based on a reflectance input. The accuracy of the parameter estimations depends on the used model, the applied inversion technique and the quality of the input data (Roosjen et al., 2018).

PROSPECT pioneered the simulation of directional–hemispherical reflectance and transmittance of various green monocotyledon and dicotyledon species, as well as senescent leaves, over the solar spectrum from 400 nm to 2500 nm ([Jacquemoud & Baret, 1990](http://www2.geog.ucl.ac.uk/~mdisney/teaching/GEOGG141/papers/jacqemoud_baret_prospect.pdf" \t "_blank)). It is based on the representation of the leaf as one or several absorbing plates with rough surfaces giving rise to isotropic scattering. The model uses two classes of input variables: the leaf structure parameter N which is the number of compact layers specifying the average number of air/cell walls interfaces within the mesophyll, and the leaf biochemical content, which has changed since the original formulation of the model ( [Fourty et al., 1996](http://www.sciencedirect.com/science/article/pii/0034425795002340" \t "_blank), [Jacquemoud et al., 1996](http://www.sciencedirect.com/science/article/pii/0034425795002383) and [Jacquemoud et al., 2000](http://www.sciencedirect.com/science/article/pii/S0034425700001395" \t "_blank)). The absorption of light by photosynthetic pigments which predominates in the visible (VIS) spectrum was long assumed to be entirely caused by chlorophylls, although carotenoids (including xanthophyll pigments) and anthocyanins may be significant in greening or senescing leaves. Its latest version is PROSPECT-4- [Feret et al. (2008)](http://www.sciencedirect.com/science/article/pii/S0034425708000813" \t "_blank) separated total chlorophylls from total carotenoids (PROSPECT-5). [<http://ipl.uv.es/artmo/index.php/radiative-transfer-models/84-rtm-leaf/1-prospect-models>]

# Inputs and outputs

* 1. **Models’ development:**
* PROSPECT, 1990 (the original version, three input parameters with others fitted with experimental data) (Jacquemoud and Baret, 1990)
* PROSPECT-4 (introduce dry matter) (Feret et al., 2008)
* PROSPECT-5 (separate chlorophylls from other segment – carotenoids and brown pigments) (Feret et al., 2008)
* PROSPECT-D, 2017 (dynamic modelling through the plant lifecycle) (Feret et al., 2017)
* SAIL, 1984 (the original version) (Verhoef, 1984)
* SAILH, 1998 (add the hot-spot effect, ) (Verhoef, 1998)
* SAIL++, 2002 (apply N+2 stream method to improve description of the multiply scattered interval radiation field) (Verhoef, 2002)
* 4SAIL2, 2007 (incorporate crown clumping effects so that it may also accommodate the modelling of forests) (Verhoef and Bach, 2007)
* 4SAIL

**Notes**: Different inputs and outputs of each version of SAIL model are listed in Table 1A.

* 1. **PRO4SAIL’s inputs and outputs**

**Source codes of model:** [**http://teledetection.ipgp.jussieu.fr/prosail/**](http://teledetection.ipgp.jussieu.fr/prosail/)

|  |  |  |
| --- | --- | --- |
|  | PRO4SAIL | |
| PROSPECT-5B | 4SAIL |
| Input | * N, leaf structure parameter * Cw, leaf water content or leaf equivalent water thickness (cm) * Cm, leaf dry matter content (g cm-1) * Cab, leaf chlorophyll-a and -b content (µg cm-1) * Car, carotenoid content (µg cm-1) * Cbrown, brown pigment content (µg cm-1) | **Solar-object-sensor geometry:**   * , solar zenith angle (deg) * , viewing zenith angle (deg) * , relative azimuth angle (deg)   **Leaf optical properties:**   * *RN, single leaf reflectance of N layers of a specific wavelength (%)* * *TN, single leaf transmission of N layers of a specific wavelength (%)*   **Soil properties:**   * *rs*, soil’s reflectance (%)   **canopy architecture:**   * LAI, leaf area index (m2 m-2) * LIDF, leaf inclination density function   (TypeLidf=1, parameter a, b;  TypeLidf=2, Parameter ALA)   * *q*, hot-spot size parameter (m m-1) |
| Output | * *RN, single leaf reflectance of N layers of a specific wavelength (%)* * *TN, single leaf transmission of N layers of a specific wavelength (%)* | rddt, bi-hemispherical reflectance factor  rsdt, directional-hemispherical reflectance factor  rdot, hemispherical-directional reflectance factor  rsot, bi-directional reflectance factor |
| PRO4SAIL’s output | resv, directional reflectance of canopy | |

**Notes:**

**(1) The leaf inclination density function (LIDF)** is defined by: . If it is assumed that the leaf’s azimuth is distributed at random, then for a random distribution of leaf orientation which gives , the LIDF is of type spherical and given by ( is the leaf zenith angle, is the leaf azimuth angle) in SAIL (Verheof, 1984).

**LIDF parameter ALA**: In early stage, it is assumed that leaf inclination distribution meets the polynomial, ellipsoidal or elliptic distribution characterized by an average leaf inclination angle (**ALA**).

**LIDF parameter a and b:** In later version of model, it is assumed that the leaf inclination obeys the beta distribution characterized by two parameters (a and b): **Parameter a** controls the average leaf inclination slope, whereas **parameter b** influences the shape of the distribution (bimodality) (Verhoef, 1998).

**(2) Hot spot effect** refers to a phenomenon that generates a peak of reflectance near the viewing direction when the observer views from the direction of incident solar ray. When hot spot occurs, the area of object is completely overlapped with its shadow and illumination background area reaches its maximum; in this case, the solar incident angle becomes the viewing angle.

The **hot spot size parameter ()** is equal to the ratio of the correlation length of leaf projection in the horizontal plane () and the canopy height (). This ratio is the only additional parameter necessary to describe the hot spot effect for a single layer canopy. Hot spot effect is primarily intended as a correction of the canopy reflection with regard to bidirectional effects. The hot spot size parameter can be estimated in two way (Verhoef, 1998):

* (*a* is an empirical constant). When leaf area index (L) increases mainly by making new leaves (i.e. wheat), it may be assumed that the canopy height grows proportionally to the leaf area index.
* (*b* is an empirical constant). When leaf area index increases primarily by letting existing leaves grow in size and making an assumption that leaves grow in area but have a constant shape, it means the height of the canopy is mainly determined by the linear size of the leaves (i.e. sugar beet).

(3) Other coefficients from experiments (dataSpec-P5B) that should be known before running model

1. wavelength(nm)
2. refractive index of leaf material (capability of changing the direction of light)
3. specific absorption coefficient of chlorophyll (a+b) (cm2.microg-1)
4. specific absorption coefficient of carotenoids (cm2.microg-1)
5. specific absorption coefficient of brown pigments (arbitrary units)
6. specific absorption coefficient of water (cm-1)
7. specific absorption coefficient of dry matter (g.cm-1)
8. direct light (Es, direct sun energy)
9. diffuse light (Ed, diffuse sun energy)
10. reflectance of dry soil (Rsoil1, dry soil reflectance property)
11. reflectance of wet soil (Rsoil2, wet soil reflectance property)
12. psoil, a ratio used to mix a dry soil and a wet soil (in main\_PROSAIL\_5B.m)

(4) some questions about matlab codes

* prospect\_5B: k ( find == 0 ) ) = eps; // replace k value with eps when k equals 0.
* Apart from the six model parameters (N, Cab, Car, Cbrown, Cw, Cm), another 11 coefficients (stored in dataSpec\_P5B.m) are also needed as input of PROSPECT-5B model to calculate leaf reflectance and transmittance. Among the 11 coefficients, are the values of the last 10 coefficients depend on the first one – wavelength?

- PROSPECT is the leaf model, and only takes 6 input parameter (Cab, Car, Cbrown, EWT, LMA, and the structure parameter N) in the 5B version. The corresponding specific absorption coefficients can be found in the dataSpec\_P5B.m along with the leaf refractive index

* Will the values of these 10 coefficients change with time or other factors?

- the properties mentioned in the dataSpec\_P5B.m are not supposed to change. However, there are a few intuitive considerations, and other non straightforward...

- soil properties can be changed, of course, depending on your prior knowledge. if you want to simulate data for a surface with well known soil reflectance, go for it and do not use these examples provided here!

- I strongly recommend that you keep the specific absorption coefficients from PROSPECT as they are. PROSPECT calibration is a complex work, and these coefficients were validated. even better, I suggest that you use the latest version including PROSPECT-D, and set anthocyanins to 0 if you are not interested in it... please refer to this article<https://www.sciencedirect.com/science/article/pii/S0034425717300962> for more information.

* What are the meaning and units of the last four coefficients ([8] = direct light, [9] = diffuse light, [10] = dry soil, [11] = wet soil)?

-[8]=Es (direct sun energy), [9]=Ed (diffuse sun energy), [10]=Rsoil1 (dry soil reflectance property), [11]=Rsoil2 (wet soil reflectance property)

- the soil properties are computed based on the mix of a dry soil and a wet soil. rsoil is computed before calling PRO4SAIL, as rsoil0 = psoil\*Rsoil1+(1-psoil)\*Rsoil2; (Rsoil1 = Dry / Rsoil2 = wet). psoil represents a ratio used to mix a dry soil and a wet soil, based on the hypothese that soils in general could be represented by such mixed spectrum. of course it is not the case, but this is just a simplified way to illustrate the possibility to adjust soil properties in a continuous fashion. if you have soil optical properties corresponding to your study of interest, I recommend you using it. if not, you may need to check online for available soil spectral libraries...

- relative contribution for direct and diffuse light is based on a certain number of hypothese (clear sky, high visibility...), and the relationship suggested by francois and taken from spitters should be adjusted accordingly if conditions do not respect these hypotheses...

- Please refer to Francois et al. (2002) "Conversion of 400–1100 nm vegetation albedo measurements into total shortwave broadband albedo using a canopy radiative transfer model" and Spitters et al (1986) "Separating the diffuse and direct component of global radiation and its implications for modeling canopy photosynthesis" for more details about SKYL…

- Here Es refers to direct sun energy and Ed refers to diffuse sun energy. Skyl represents the proportion of diffuse energy, so that the direct photosynthetically active radiation corresponds to (1-skyl)\*Es, and so on. then the directional reflectance has two components, direct reflectance, which is weighted by PARdiro, and diffuse reflectance, which is weighted by PARdifo...

* What are these four functions (dcum, Jfun1, Jfun2, Jfun3) used for as I don’t find the citation of these functions?

-Some of the functions are used to avoid singularities. Please refer to the papers from Verhoef et al to get the full understanding of the SAIL model.

# Data source

The data that the model needs is spectra information – reflectance.

1. Field measurement with handheld equipment
2. Images captured from satellite

Remote sensing data now can achieve very high spatial and temporal resolution; for example, ZY-3 MUX data has a spatial resolution of 5.8 meter and a revisit time of 5 days (Zhao et al., 2018).

1. Images collected from UAV

# Inversion and its methods

**(1) Inversion processes**

In the inversion process, we generally fix the non-target parameters with certain values in advance based on experimental data and then use the reflectance as input to simultaneously back calculate those parameters that we want to estimate.

**(2) Inversion methods**

There are mainly three inversion methods: (1) numeric optimization (NO), (2) look-up table (LUT), (3) machine learning (ML) methods with neural networks (NN) as the most representative (Wu & Qin, 2018). The selection of inversion method is a trade-off of accuracy and efficiency.

* **Numeric optimization**

Determining the optimal set of parameter space that minimizes a merit function (also named cost function) which measures the distance between calculated (from model) and measured (from images or manual measurements) reflectance or other indices. The key point is to determine the measurement standard of optimization, for example, minimizing the RMSE of calculated and measured values (Z. H. Li et al., 2018; Roosjen et al., 2018) .

* **Look-up table**

Establish a lookup table where values of parameters and corresponding reflectance value are existent in pair, then we can quickly find the estimated values of targe parameters by searching the table with determined reflectance value. The problem is to determine how big a table can meet the requirement of accuracy and assure it won’t take a long time to find out the answer from the built table.

* **Machine learning**

**(3) inversion accuracy**

The accuracy depends on the used model, the applied inversion technique, and the quality of the input data.

LAI 的反演需要输入其他参数，这些参数的取值不够准确或者反演方法和模型不够好，从而导致LAI的反演精度不够高，那么将无法应用于后续的一系列研究中。

Why do we want to reverse LAI?

In order to obtain the LAI of a region simultaneously.

What can we do after that?

Obtain more detail growth conditions of crops in the region according to LAI difference within region, which can help optimize management.

Those traits should be highly related to LAI; otherwise, the modelling results based on LAI won’t make sense. 就是说合不合适取决于这些特征的差异是否反映在LAI上。

# Remaining problems and possible solutions

1. Model uncertainties

* Model is an approximation of the real condition.
* *Impacts of viewing zenith angle.* The introduction of more viewing angles, more well distributed viewing angles, and viewing angles up to larger zenith angles can improve the accuracy of LAI estimations by inversion of PROSAIL model (Roosjen et al., 2018).

1. Measurement uncertainties
2. Non-unique inversed results

The issue of interaction between parameters may lead to that two different combinations of the parameters giving similar reflectance values, making the solution of the inverse problem non-unique (C Bacour et al., 2002). To reduce the number of possible solutions to the inversion of a RTM model, regularization needs to be applied. This can for example be done by constraining parameters, or by the use of a priori information on the parameters (Laurent et al., 2014; Mousivand et al., 2015). Another way to improve the estimation of vegetation parameters is by increasing the dimensionality of the input data by introducing multi angular observations (Dorigo, 2012; Schaepman et al., 2005; Vuolo et al., 2008; Weiss et al., 2000) (Roosjen et al., 2018). It is also possible to overcome this non-unique solution problem by averaging the similar parameter combinations which generates the smallest differences between calculated and measured reflectance (or vegetation indexes) (H. Li et al., 2018).

# Application

Classical applications in early stage:

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Data source | Resolution | Centre wavelength (bandwidth) (nm) | Models | Number of viewing directions | Plants | Estimated variables | Inversion method | Reference |
| POLDER  (airborne data) | 20m\*20m | 550,670,865 (40) | PROSECT + SAIL/ KUUSK/IAPI | 14 | Wheat, maize, sunflower, alfalfa | LAI, ϴl, Sl, αsoil, Cab | Numeric optimization | (Cédric Bacour et al., 2002) |
| POLDER  (spaceborne data) |  | 443,550,670,865 (40) | PROSECT + SAIL/ KUUSK/IAPI/NADI | 13 |  | LAI, ϴl, Sl, αsoil, Cab, N |  | (Bacour, Jacquemoud, Tourbier, Dechambre, & Frangi, 2002) |

|  |  |  |
| --- | --- | --- |
| Main results about LAI | Key aim | Reference |
| PROSAIL's estimated accuracy of wheat LAI decreased with time based on mapping results. On average, this characteristic is not obvious. | Focus on validating the capability of PROSAIL inversion for estimating vegetation index. | (Cédric Bacour et al., 2002) |
| The LAI (in INR), Cab (VIS) and mean leaf inclination angle (or LAD, leaf angle distribution) are the parameters most significantly impacting the reflectance. | Focus on validating the sensitivity of PROSAIL to input parameter. | (C Bacour et al., 2002) |

Some latest applications (2018):

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Data source | Spatial resolution | Centre wavelength (bandwidth) or range (nm) | Models | Number of viewing directions | Plants | Estimated variables | Inversion methods | Reference |
| SPOT-5  (space-borne data + manual measurements) | 10m  (SWIR is 20m and resampled into 10m) | 500-590(G), 610-680(R), 780-890(NIR), 1580-1750(SWIR) | PROSECT + SAIL | 1 | No concrete classification | LAI | Look-up table | (Zhu, Li, & Tang, 2018) |
| ZY-3 MUX, GF-1 WFV, HJ-1 CCD  (space-borne data + manual measurements) | 5.8m,  16m,  30m | 630-690 /770-890,  639-690 /770-890,  630-690 /760-900 | PROSECT-5B + SAILH | 1 | maize | LAI | Look-up table | (Zhao et al., 2018) |
| UAV  (air-borne data + manual measurements) | 5m | 500.2 (25.6)  547.0 (26.4)  558.8 (26)  568.8 (25.8)  657.6 (26)  673.6 (26.4)  705.8 (26.2)  739.0 (38.8)  782.8 (37)  791.6 (36.8)  810.3 (36.2)  829.0 (35.6)  847.8 (35.2)  864.7 (34.8)  878.7 (35.6)  894.7 (34.2) | PROSECT + SAIL | multiple  (two schemes) | potato | LAI, LCC | Numeric optimization | (Roosjen et al., 2018) |
| Sentinel-2A  (space-borne data + manual measurements) | 10m | 490,  560,  665,  842 | PROSECT + SAIL |  | pasture | LAI, biomass | Look-up table | (Punalekar et al., 2018) |
| Only manual measurements at multiple growth stages |  |  | N-PROSECT + SAIL |  | wheat | Leaf nitrogen concentration (LNC), canopy nitrogen density (CND) | Numeric optimization | (Z. H. Li et al., 2018) |
| GF-1 WFV  (space-borne data + manual measurements) | 16m | 450-520(B),  520-590(G),  630-690(R),  770-890(NIR) | PROSECT + SAIL | 2 | wheat | LAI | Look-up table | (Li, Liu, Liu, Chen, & Huang, 2018) |

|  |  |  |
| --- | --- | --- |
| Main results about LAI | Key aim | Reference |
| Reversion results (June 12 to 14) are suitable for crop LAI estimation, with a root mean square error (RMSE) of ∼0.31m2∕m2 and determination  coefficient (R2) of 0.65. | whether it is suitable to retrieve LAI from SPOT image based on look-up-table which is generated by the PROSAIL model. | (Zhu et al., 2018) |
| ZY-3 MUX is the best one for estimating LAI. | Compare the accuracy of three data for estimating LAI based on the relationship of VI and LAI values that were generated from LUT inverted from PROSAIL model. | (Zhao et al., 2018) |
| Multi-angular observations can improve the estimation of LAI and LCC by inversion of PROSAIL model | Study the potential of multi-angular measurements collected by UAVs for the retrieval of LAI and LCC by inversion of PROSAIL model | (Roosjen et al., 2018) |
| For LAI,  RMSE 0.55- 1.19 m2 m-2;  R2 0.56-0.87 | whether a Look Up Table (LUT) based  radiative transfer model inversion algorithm is able to reliably estimate  LAI over diﬀerent types of pastures | (Punalekar et al., 2018) |
| For LNC, R2 = 0.75, RMSE = 0.38%;  For LNC, R2 = 0.82, RMSE = 0.95 g m-2.  (*LNC, leaf nitrogen concentration;*  *CND, canopy nitrogen density)* | Try to retrieve crop N status both at leaf and canopy scales by reversion of N-PROSAIL model. | (Z. H. Li et al., 2018) |
| Best strategy during different stages:  (1) Elongation stage: the LUT strategies of LAI-GNDVI (RMSE=0.34, R2=0.61)  (2) Grain-filling stages: LAI-Green (RMSE = 0.74,  R2 = 0.20) | Compare the performances of LAI-LUT strategies with different bands of reflectance to estimate LAI | (H. Li et al., 2018) |

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# Appendix

Table A1 Summary of inputs and outputs of SAIL model

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Model | | SAIL | SAILH | SAIL++ | 4SAIL2 | 4SAIL |
| Reference | | Verhoef, 1984, 1998 | Verhoef, 1998 | Verhoef, 2002 | Verhoef and Bach, 2007 | ?refer to the model available online |
| Highlight | |  | Introduce hot spot effect and change LIDF expression to improve its flexibility on the base of SAIL. | Introduce the N+2 stream theory to justify the simplication of the multiple scattering calculation applied in SAILH. | Treat soil as non-Lambertian to calculate its reflectance based on BRDF model and introduce clumping effect of forest. | ? |
| inputs | **Sun-object-sensor geometry** | | | | | |
| **,** solar zenith angle (deg) | √ | √ | √ | √ | √ |
| , viewing zenith angle (deg) | √ | √ | √ | √ | √ |
| , relative azimuth angle (deg) | √ | √ | √ | √ | √ |
| **Leaf optical properties** | | | | | |
| **ρ**, single leaf reflectance (%) | √ | √ | √ | **ρg**, green leaf reflectance (%)  **ρb**, brown leaf reflectance (%) | ? √ |
| **τ**, single leaf transmission (%) | √ | √ | √ | **τg**, green leaf transmission (%)  **τb**, brown leaf transmission (%) | ? √ |
| **Soil properties** | | | | | |
| ***rs***, soil’s reflectance assumed as Lambertian | √ | √ | √ | ***Soil BRDF properties (soil as a non-Lambertian)***  rso, bi-directional reflectance factor  rdo, hemispherical-directional reflectance factor  rsd, directional-hemispherical reflectance factor for solar incident flux  rdd, bi-hemispherical reflectance factor | ? √ |
| **Canopy architecture** | | | | | |
| **L**, leaf area index | √ | √ | √ | √ | √ |
| **LIDF**, leaf area inclination density function. | **Parameter: distribution type and ALA.** It is assumed that leaf inclination distribution obeys polynomial, ellipsoidal or elliptic distribution characterized by an average leaf angle (ALA). | **LIDF parameter a and b**  The leaf inclination distribution is approximated by Beta distribution characterized by parameters a and b. | **LIDF parameter a and b** | **LIDF parameter a and b** | **TypeLidf=1, parameter a, b;**  **TypeLidf=2,**  **Parameter ALA** |
| **q**, hot spot size parameter (q= , a ratio of correlation length of leaf projection on the horizontal plane and canopy height. ) | × | √ | √ | √ | √ |
| **fB**, fraction brown leaf area | × | × | × | √ | × |
| **D**, layer dissociation factor | × | × | × | √ | × |
| **Cv**, vertical crown cover percentage | × | × | × | √ | × |
| , tree shape factor | × | × | × | √ | × |
| outputs |  | canopy reflectance ? | canopy reflectance ? | canopy reflectance ? | canopy reflectance ? | ? |
|  |  |  |  |  |  |