CROP STRUCTURE AND LIGHT MICROCLIMATE

Characterization and applications

Editors

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Estimating vegetation biophysical parameters by inversion of a reflectance model on high spectral resolution data

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Introduction

High spectral resolution is a quite new domain in remote sensing. Until these last years, technological limitations prevented us from measuring the spectral radiance of terrestrial targets. From now on, field or airborne spectroradiometers, such as AVIRIS, GER64, PMI are available and can provide reflectance spectra in the optical domain (from 400 nm to 2500 nm) with a resolution approaching some nanometers. If measuring the spectral reflectance of a plant canopy is nowadays possible, the tools that would allow us to analyse a spectrum acquired on vegetation to retrieve canopy parameters are still unknown. Three approaches are used to achieve this goal :

The statistical approach consists in creating a catalogue of reference spectra acquired in laboratory or in field on well known surfaces. Then, the spectral analysis amounts to determining the best combination of these spectra which characterizes the target (Boardman, 1990; Adams *et al.*, 1991). This method is frequently used in geology where effects are additive; on vegetation, it can only provide qualitative information insofar as processes are rarely simply additive.

The semi-empirical approach consists in relating spectral indices to some canopy characteristics. This is the case of vegetation indices (Baret and Guyot, 1991) commonly used in remote sensing. But high spectral resolution has also permitted the development of specific tools based on shape analyses of reflectance spectra. Thus, Leprieur and Baret (1991) approximated the part of the spectrum ranging from 1550 nm to 1750 nm by a parabola arc and have shown that the convexity depends on leaf water content, canopy architecture and soil reflectance. Other authors (Baret *et al.*, 1991; Demetriades-Shah *et al.*, 1990; ...) studied the red edge, which corresponds to the great increase of reflectance from (650 nm) to near infrared (800 nm). As for vegetation indices, empirical relationships have been established between leaf or canopy variables and the position of the inflexion point λ_i characterizing this transition.

The inversion of physical models consists, first, in describing the interactions between sun light and canopy (leaf+soil) through an analytical reflectance model (Goel, 1989). Once this model has been validated on experimental data sets, the inversion procedure, that is the estimation of canopy biophysical variables from reflectance measurements, will be possible. We will distinguish two methods for the inversion :

- A first method using directional data allows to estimate the biophysical variables describing canopy architecture. Goel and Thompson (1984a, 1984b) shown that LAI and, with less accuracy, leaf inclination θ_l, could be estimated by inversion of the SAIL model (Verhoef, 1984, 1985). Verstraete *et al.* (1990), Pinty *et al.* (1990) also estimated leaf optical properties as well as their spatial distribution by inverting an analytical model of directional reflectance.

- A second method using spectral data acquired for example at nadir, would permit to extract canopy spectral information but also, under certain conditions, variables describing its structure. Until now, the number of wavebands available on satelite sensors was smaller than the number of canopy parameters that determine its reflectance. Inversion using nadir reflectances in several wavelength bands was inaccurate (Goel, 1989). However, at leaf scale, such an inversion was already tested to determine the internal structure of mesophyll, chlorophyll concentration and water content (Andrieu *et al.*, 1988; Jacquemoud and Baret, 1990; Yamada and Fujimura, 1990) from reflectance or transmittance spectra acquired with a laboratory spectrophotometer.

This article presents how high spectral resolution can be used to estimate canopy biophysical parameters by model inversion. Modelling canopy spectral radiance requires:

- a leaf optical properties model
- a soil optical properties model
- a canopy reflectance model

In this paper, we will consider that the soil is perfectly known because modelling its optical properties introduces too many parameters (Jacquemoud *et al.*, 1991). We will first focus on leaf optical properties model and its inversion. Then, we will discuss problems connected with the inversion process of canopy reflectance model from high spectral resolution data, from both synthetic and actual data.

1. Leaf optical properties

1.1 The *PROSPECT* model

PROSPECT (Jacquemoud and Baret, 1990) is a radiative transfer model simulating leaf optical properties as a function of three variables : a parameter which describes mesophyll internal structure , N, a chlorophyll a+b concentration expressed in μg cm^{-2}, C_{ab}, and a water thickness expressed in cm, C_e. Spectral variations of reflectance or transmittance are determined by the refractive index of plant materials, $n(\lambda)$, the specific absorption coefficients of chlorophylls, $k_{ab}(\lambda)$, and water, $k_e(\lambda)$, and finally a coefficient $k_0(\lambda)$ characterizing the low absorption of an albino (without pigments) and dry (without water) leaf. This model has been validated on three independent data sets. We have shown its ability to simulate with a good accuracy the leaf optical properties (Fig. 1).

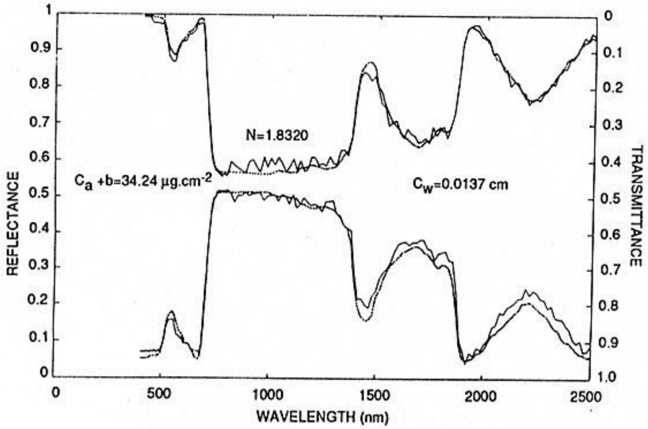

Figure 1. Comparison of spectral reflectance and transmittance modelled (...) and measured (—) for green soybean.

1.2 Model inversion

The model sensitivity analysis shown that, when absorption is low (548 nm and near infrared), leaf reflectance and transmittance strongly vary as a function of the structure parameter N. When absorption is high (450 nm and 672 nm), leaf optical properties are very little sensitive to N. Therefore, fitting the N parameter will be optimal in the near infrared. Determination of chlorophyll a+b concentration and water thickness depend on their level : for low concentrations, the sensitivity is maximum in strong absorption domains (450 nm, 672 nm, 1450 nm, 1950 nm and 2500 nm); for high concentrations, it is the contrary (548 nm, red edge, 1684 nm and 2211 nm). This shows the capability of high spectral resolution to retrieve, with a good accuracy, leaf biophysical parameters (N, C_{ab}, C_e), independently of their level.

Inversion of *PROSPECT* model consists in adjusting the set of parameters $P = (N, C_{ab}, C_e)$ which minimizes Δ^2 on the whole spectrum :

$$\Delta^2 = \sum_{\lambda} (R^2 + T^2) \qquad (1)$$

with $R = R_{mes}(\lambda) - R_{mod}(\lambda,P)$ and $T = T_{mes}(\lambda) - T_{mod}(\lambda,P)$. The routine HAUS59 which minimizes a function using the Marquardt (1963) algorithm was chosen for this purpose. Retrieved values of C_{ab} and C_e agree with values measured by direct biochemical and physical methods. The root mean square (rms) is 3.669 μg cm^{-2} for chlorophyll concentration and 0.0029 cm for water equivalent thickness.

The radiative transfer model, *PROSPECT*, is then easily invertible. It allows to estimate leaf biophysical characteristics rapidly and with optical-non destructive methods.

2. Canopy optical properties

Similarly to the leaf, we used a radiative transfer model for canopies. The canopy reflectance model we used describes in a simple way canopy structure. It requires only few parameters which makes easier the inversion process. Our simulations have been carried out with the SAIL model (Verhoef, 1984, 1985). Coupling *PROSPECT* and *SAIL* models permits to simulate plant canopy reflectance spectra in the optical domain. In this preliminary step which aims evaluating the possibilities to invert models of canopy spectral reflectance, we will assume that soil optical properties are well known. Canopy reflectance depends on the following parameters :

- biochemical parameters : chlorophyll a+b concentration (C_{ab}), water thickness (C_e), leaf internal structure (N), leaf area index (LAI) and average leaf inclination (θ_l);
- soil spectral reflectance ($\rho_s(\lambda)$) assumed lambertian;
- external parameters : zenith (θ_o) and azimuth (ψ_o) viewing angles, zenith illumination angle (θ_s) and fraction of diffuse incident radiation (Skyl).

Before studying the inversion process, we may analyze rapidly the sensitivity of the model to canopy biophysical characteristics.

2.1 Sensitivity analysis

We choose a simple measurement configuration : nadir viewing ($\theta_o = 0$, $\psi_o = 0$), $\theta_s = 40°$ and Skyl = 0.1. We consider the mean data set $C_{ab} = 32$ μg cm^{-2}, $C_e = 0.0255$ cm, LAI = 3 and $\theta_l = 45°$. We let vary each of the biophysical parameter separately. Soil background spectrum is known and presented in figure 2c.

Figure 2a shows that a variation of leaf structure parameter N induces little canopy reflectance variations on the whole spectrum. Chlorophyll a+b absorbs light in the visible, water in the middle infrared (Fig. 2b). The absorption domains of these two foliar constituents are completely separated. Sensitivity of canopy reflectance to C_{ab} or C_e is the same to that observed at the leaf scale : we distinguish domains of strong absorption (low reflectance) very sensitive to low concentrations, and domains of low absorption, the most sensitive to high concentrations. Leaf area index and average leaf inclination determine reflectance levels in the near infrared, and more generally in the other optical domains (Fig. 2c et 2d). We notice that increasing LAI amounts to decreasing θ_l. Nevertheless, these phenomena are not totally symmetrical : thus, in the blue and red, canopy reflectance rapidly reaches a limit with LAI; this is not the case with θ_l. These simulations allow us to test the relative influence of each of the input parameters. We notice that the sensitivity of canopy reflectance to each of these biophysical parameters vary both with wavelength and the values of the other parameters. It should be possible to invert the model and estimate the set of optimal parameters corresponding to the measured spectrum.

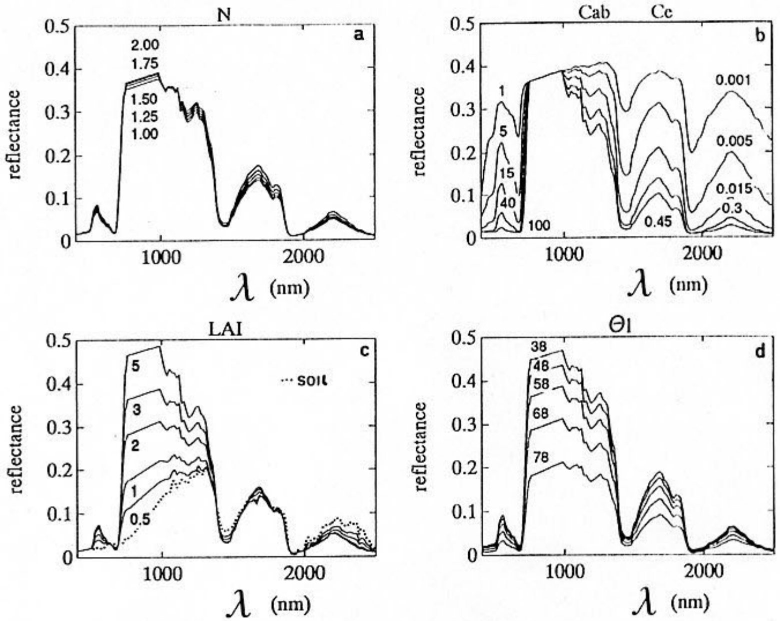

Figure 2. Variations of canopy reflectance spectra as a function of mesophyll internal structure (N), chlorophyll a+b concentration (C_{ab}), water thickness (C_e), leaf area index (LAI) and geometry of the canopy (θ_l). Figure 2c presents the soil spectrum used in the simulations.

2.2 Inversion on synthetic spectra

2.2.1 Invertibility of the model

Is the *SAIL* model totally and mathematically invertible? To answer this question, we simulated canopy reflectance spectra, taking for each parameter its maximum, minimum and average values (Table 1). It corresponds to $3^5 = 243$ different spectra.

Table 1. Canopy parameters used to simulate synthetic spectra. The average set is the initial set for the inversion : $\theta_s = 40°$, $\theta_o = 0°$, $\psi_o = 0°$ and Skyl = 0.1. The soil spectrum is presented in Figure 2c.

N	C_{ab} (μg cm^{-2})	C_e (cm)	LAI	θ_l
1.0	2	0.0010	1	25°
1.5	32	0.0255	3	45°
2.0	62	0.05	5	65°

One can immediately notice that 200 spectral wavebands are not necessary to estimate 5 parameters. There is a large redundancy and, from a theoretical point of view, 5 independent wavebands should be enough. Reducing the number of spectral wavebands is a problem which has not yet found any solution at the moment : this is the reason why, we will keep all the spectral information in this study. As at the leaf scale, we used HAUS59 routine to estimate model parameters. For all the cases, the inversion process converged toward the original values of canopy parameters, suggesting that the *PROSPECT+SAIL* model used in spectral mode is **totally and mathematically invertible.** That means that, in theory, we can determine all canopy parameters using only a reflectance spectrum acquired at nadir.

2.2.2 Unicity of the parameters

In order to test the sensitivity of the parameters retrieved by inversion, we performed the following computations : let us consider the average data set N = 1.5, $C_{ab} = 32\ \mu g\ cm^{-2}$, $C_e = 0.0255$ cm, LAI = 3 and $\theta_l = 45°$. We simulate the corresponding reflectance spectrum; then, we invert the model assuming that one of the 5 parameters is kept fixed, for example the LAI, at a value close to its initial value (LAI + δLAI). Results are presented in table 2. The 5 spectra calculated from the 5 data set cannot be visually separated. Figure 3 presents the deviation from the mean spectrum.

The chlorophyll a+b concentration and water depth are relatively stable. On the other hand, decreasing LAI amounts to increasing leaf structure parameter N and decreasing the average leaf angle θ_l. We then inverted the 5 spectra, all of the parameters beeing free : we find again the initial sets of parameters, in accordance with the previous results. In conclusion, these tests show that, mathematically, there is a bijection between the set of parameters and the set of spectra. However, several different sets of parameters can correspond to spectra almost similar; this let expect future difficulties when noisy or actual spectra are to be used.

Table 2. Inversion of the average spectrum keeping fixed the LAI.

N	C_{ab}	C_e	LAI	θ_l	rms
1.899	35.44	0.02796	**2**	24.11	$3.50\ 10^{-4}$
1.688	33.49	0.02649	**2.5**	35.78	$7.42\ 10^{-5}$
1.5	**32**	**0.0255**	**3**	**45**	0
1.321	31.03	0.02498	**3.5**	51.98	$5.83\ 10^{-5}$
1.121	31.07	0.02533	**4**	57.17	$2.09\ 10^{-4}$

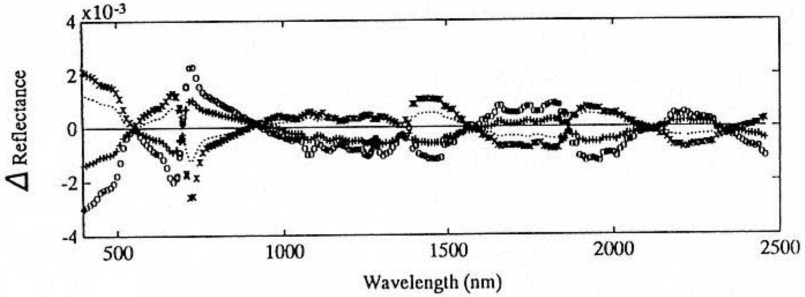

Figure 3. Deviation between the spectrum calculated by the set of parameters $(N, C_{ab}, C_e, LAI, \theta_l) = (1.5, 32, 0.0255, 3, 45)$ and spectra calculated by the 4 other sets presented in table 3.

2.2.3 Noisy data

Actual data are more often noisy. To what extent the accuracy of the inversion process can be affected by this noise? We added to each reflectance value of the synthetic spectrum, a random noise simulating the noise of a sensor. Let ρ be the simulated reflectance and ρ^* the noisy reflectance :

$$\rho^* = \rho\,(1 + N(0,1)\sigma) \tag{2}$$

Table 3 shows the results of model inversion for two levels of the relative noise level (σ) : $\sigma = 0.01$ and $\sigma = 0.05$. In order to avoid inconsistent cases corresponding to local minima, the fitted values given in table 2 are the modes of the distributions of the fitted values. We notice that, with a relative noise level (σ) of 0.05, the inversion procedure provides retrieved parameters very close to the initial parameters. That encourages us to test this approach on field spectra.

Table 3. Inversion on noisy spectra. The number of successfull cases if 237 for $\sigma = 0.01$ and 215 for $\sigma = 0.05$ (over 243 cases).

N		1	1.5	2
	$\sigma = 0.01$	0.9966	1.5557	2.0009
	$\sigma = 0.05$	0.9996	1.6997	2.013
C_{ab}		2	32	62
	$\sigma = 0.01$	1.9702	31.5532	62.0083
	$\sigma = 0.05$	1.8882	31.9241	61.8553
C_e		0.001	0.0255	0.05
	$\sigma = 0.01$	0.001	0.0250	0.0489
	$\sigma = 0.05$	0.0009	0.0255	0.0499
LAI		1	3	5
	$\sigma = 0.01$	1.0197	3.0475	4.8386
	$\sigma = 0.05$	1.0051	3.0553	5.0063
θ_l		25	45	65
	$\sigma = 0.01$	25.0018	46.0593	65.5856
	$\sigma = 0.05$	25.3471	44.9019	64.9263

2.3 Inversion on field spectra

We applied the former inversion procedure on sugar beet (*Beta vulgaris* L) canopy spectra acquired in 1989 in Brooms Barn (Malthus *et al.*, 1989). We used the IRIS field spectroradiometer (FOV = 3° x 6.5°, 975 spectral wavebands from 350 nm to 2500 nm). Measurements were performed on 24 different plots, on three different types of soils : the Brooms Barn natural soil (24 measurements), very dark peat (24 measurements) and highly reflecting dry sand (3 measurements) : 51 spectra were then available. In each plot, biophysical variables were measured: water content, chlorophyll a+b concentration, leaf area index and average leaf inclination.

2.3.1 Validation of the model

Before inverting the model, we must be sure that it simulates with a good accuracy canopy reflectance spectral variation, using the measured agronomic variables.

Unfortunately, the N parameter, calculated from leaf optical properties and θ_l were available only for three plots : we could not validate completely the model. Leaf structure parameter N vary between 1.1141 and 1.3998. We fixed it to its mean value N = 1.266. This is not very important because of the low sensitivity of canopy reflectance to this parameter (Fig. 2a). Determining with a good accuracy the average leaf ιξγμιξαυιοξ θ_l is a tedious work : the values, evaluated over three plots vary from 40° to 56° with an average of 47°1. If one remembers the great sensitivity of canopy reflectance to θ_l (Fig. 2c), particularly in the near infrared, it is not possible to take this mean value for the plots where direct measurements have not been performed. Then, we first inverted the model by fitting the θ_l value. 4 attempts of model inversion over 51 did not end. They correspond to a low LAI (LAI = 0.15). These failures can be attributed to wrong soil optical properties or aggregation problems not taken into account though *SAIL* model hypotheses. The average fitted θ_l value (46°7) is very close to the measured average (47°1). We will assume that these values are effectively the values of the plots.

2.3.2 Inversion of the model

If we retrieve concurrently all canopy parameters, we observe a very good fit of the measured spectra (rms < 0.05) but N, LAI and θ_l values are totally inconsistent. Fears expressed in the previous section concerning the interdependency between the retrieved parameter values is confirmed. On the other hand, the estimation of chlorophyll concentration and water thickness aggrees, quite well, with the measured values ($C_{ab\text{-fitted}} = 34.48\ \mu g\ cm^{-2}$, $C_{ab\text{-measured}} = 33.17\ \mu g\ cm^{-2}$; $C_{e\text{-fitted}} = 0.0293$ cm, $C_{e\text{-measured}} = 0.0332$). Some constraints must be necessary introduced in order to stabilize the inversion procedures. For example, the sensitivity study has shown a limited influence of the structure parameter N on the canopy reflectance : we will fix it to its mean value N = 1.266. Moreover, LAI and θ_l parameters which seemed very linked won't be estimated simultaneously : we decided to set the average leaf angle to the values previously fitted. Results of the inversion are presented in figures 4, 5 and 6.

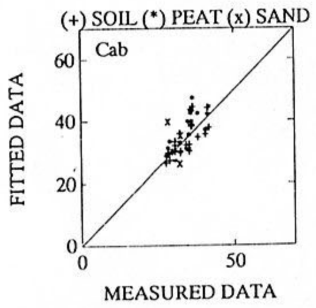

Figure 4. Comparison between the measured and fitted chlorophyll a+b concentration.

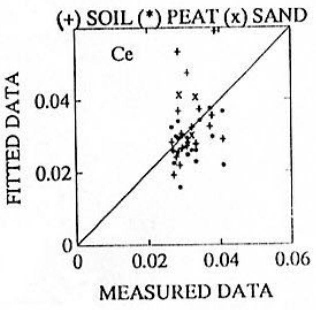

Figure 5. Comparison between the measured and fitted water depth.

Figure 4 shows off that chlorophyll a+b concentration can be estimated with a good accuracy from canopy spectra. The case of water content is more complicated (Fig. 5), particularly for the natural soil of Brooms Barn for which moisture content and surface roughness varied presumably from one measurement to another. Finally, LAI is estimated with an acceptable accuracy (Fig. 6).

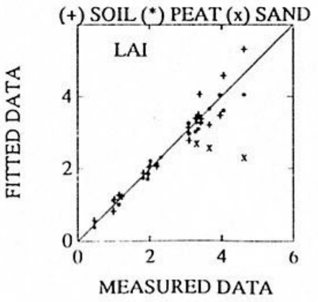

Figure 6. Comparison between measured and fitted leaf area index.

Conclusion

We shown that *PROSPECT+SAIL* model was mathematically and totally invertible. It means that, in theory, one can estimate the biophysical variables of a canopy from one reflectance spectrum acquired at nadir. Unfortunately, reality is more complex : radiometric measurements always contain errors; moreover, the *SAIL* model, like every canopy reflectance model, is a simplified description of canopy structure and photons transport inside vegetation. All of these reasons make difficult the inversion process and its interpretation.

Direct measurement of canopy biophysical variables is also sometimes criticable. For example, the the leaf chlorophyll concentration determination largely depends on the extracting method and the representativeness of leaf samples is often limited; concentration deviations higher than 5 μg cm^{-2} on the same sample are observed frequently. Measurement of leaf area index or leaf inclination can be rather inaccurate. For example, in the case of sugar beet, θ_l vary during the day as a function of climatic conditions. Remembering reflectance high sensitivity to these variables, we now better understand the discrepancies observed between measured and fitted values.

We limited our analysis to the case where soil was perfectly known. However, it rarely happends in operational conditions. Future studies have to investigate inversion of canopy reflectance models taking into account the fitting of parameters characterizing soil optical properties.

Finally, at the beginning, we presented two inversion methods of remote sensing data: a third method may consist in combining directional and spectral data in order to access all of the canopy information. This work would deserve to be continued using more precise and complete data sets. We shown that, under certain assumptions, it was possible to retrieve canopy variables of agronomical and ecological interest. A lot of work on high spectral resolution will still be necessary to interpret this new source of data.

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