

# Use of Spectral Analogy To Evaluate Canopy Reflectance Sensitivity to Leaf Optical Properties

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**T**he spectral variation of canopy reflectance is mostly governed by the optical properties of the elements such as the leaves. Since leaf intrinsic scattering properties show very little spectral variation, leaf optical properties are related to their absorption properties. Spectral analogies are thus observed between two wavelengths for which the optical properties (absorption, reflectance, or transmittance) of the elements are similar. The red edge for green plants shows the full range of variation of leaf optical properties. The relationship between canopy reflectance and leaf reflectance measured concurrently at the red edge over sugar beet canopies was thus used to simulate canopy reflectance over the whole spectral domain from leaf reflectance spectra measured over the whole spectral domain. The results show that the spectral analogies found allows accurate reconstruction of canopy reflectance spectra. Explicit assumptions about the very low spectral variation of leaf intrinsic scattering properties are thus indirectly justified. The sensitivity of canopy reflectance ( $\rho_c$ ) to leaf optical properties is then investigated from concurrent spectral variations of canopy ( $\partial\rho_c/\partial\lambda$ ) and leaf reflectance ( $\partial\rho_l/\partial\lambda$ ):  $\partial\rho_c/\partial\rho_l = (\partial\rho_c/\partial\lambda)(\partial\rho_l/\partial\lambda)^{-1}$ . This expression is strictly valid only when the optical properties of the soil background or of the other vegetation elements such as bark are either spectrally flat or do not contribute significantly to canopy reflectance. Simulations using the SAIL and PROSPECT models demonstrate that

the sensitivity of canopy reflectance to leaf reflectance is significant for large vegetation cover fractions in spectral domains where absorption is low. In these conditions, multiple scattering enhances the leaf absorption features by a factor that can be greater than 2.0. To override the limitations of the SAIL model for the description of the canopy architecture, we tested the previous simulation results on experimental data. Concurrent canopy and leaf reflectance spectra were measured for a range of sugar beet canopies. The results show good agreement with the theoretical findings. Conclusions are drawn about the applicability of these findings, with particular attention to the potential detectability of leaf biochemical composition from canopy reflectance sensed from space.

## INTRODUCTION

Investigations on the use of high spectral resolution information have been made only recently with the latest technological advances in the field of imaging spectroscopy. Ground level experiments as well as airborne experiments using spectrophotometers indicate some potential use for canopy biochemistry assessment. For example, Baret and Jacquemoud (1993) retrieved leaf concentrations of strong absorbers such as chlorophyll or water from inversion of canopy reflectance models.

Reflectance in several narrow wavelength bands measured over various canopies (mostly forests) were also correlated to the biochemical content of minor absorbers such as lignin or nitrogen (Peterson et al., 1988). Canopy biochemical composition (mainly, lignin, cellulose, or nitrogen content) was estimated with reasonable accuracy. These results derived from the spatial covariability between vegetation reflectance spectra and

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the corresponding leaf biochemical composition. However, because of their statistical nature, the causality and indeed the portability of these relationships are questionable. They may result largely from the covariance of the biochemical contents with some radiometrically meaningful variables such as canopy structure. Since biochemical composition of the canopy depends strongly on the species as well as on canopy structure, the question still remains unsolved. The understanding of the physical processes governing leaf and canopy spectral response is required to properly address this issue (Peterson, 1991).

On the other hand, Price (1992) statistically analyzed a wide range of canopy reflectance spectra sensed from space. He demonstrated that any spectrum could be explained by a limited number of wavebands. It seems therefore that the spectral information is characterized by considerable redundancy. Knowledge about the potential detectability of leaf or soil absorption features will help to evaluate the actual dimension of the spectral information. Thus, determination of the optimal specifications for the next generation of space sensors will be possible.

Conversion processes such as fluorescence are negligible as compared to scattering processes. It follows that canopy reflectance  $\rho_c$  is a function of i) structural variables  $S$  such as leaf area index, leaf inclination, leaf size and dispersion, ii) view and source configuration ( $\Theta$ ), and iii) optical properties of the leaves [ $O_l(C)$ ], soil background ( $\rho_s$ ) or other vegetation elements ( $O_b$ ) such as bark, stems, fruits:  $\rho_c = \rho_c(S, \Theta, \rho_s, O_l(C), O_b)$ , where leaf optical properties depend obviously on leaf biochemical composition  $C$ . Canopy reflectance sensitivity to leaf biochemical composition is the product of canopy reflectance sensitivity to leaf optical properties and the sensitivity of leaf optical properties to leaf biochemical composition:

$$\frac{\partial \rho_c}{\partial C} = \frac{\partial \rho_c}{\partial O_l} \frac{dO_l}{dC} \quad (1)$$

The second term of Eq. (1),  $dO_l/dC$ , may be approximated by observed variations of the leaf optical properties with leaf biochemical composition changes, while the leaf structure governing the scattering remains unchanged. Because of this important limitation, the development of a leaf optical property model that accounts explicitly for leaf biochemical composition is required. Sensitivity analysis of the leaf model will eventually provide the  $dO_l/dC$  term.

In this article, we mainly focus on the first term of Eq. (1),  $\partial \rho_c / \partial O_l$ , corresponding to canopy reflectance sensitivity to leaf optical properties. It may be derived directly from canopy reflectance models. In the first part, we present some results gathered from simulations with the SAIL model (Verhoef, 1984; 1985). However, canopy modeling requires intensive effort to account

for the complexity of the structure of the vegetation. Most models suffer from limitations generated by approximations in the description of canopy architecture. Another approach based on experimental observations may also answer the question. Experimental data gathered during a Franco-English experimental campaign are used to illustrate the potential of this second approach.

## THEORY AND MODEL SIMULATIONS

### The Spectral Analogy for Canopy Reflectance

Leaf optical properties depend on both the surface feature and internal structure of leaves, biochemical composition, distribution of the constituents, and the complex refraction index of these constituents. The real and imaginary parts of the refraction index describe, respectively, the intrinsic scattering and absorption properties of leaf materials. As demonstrated earlier (Jacquemoud and Baret, 1990), the real part of the refraction index varies only slightly with wavelength over the whole optical domain 400–2500 nm. This is confirmed by laboratory observations over a wide range of materials (Wolfe and Zissis, 1978). Therefore, the main source of spectral variation of leaf optical properties is the imaginary part of the refraction index that corresponds to the absorption coefficient. It follows that, for a given leaf structure, leaf optical properties such as reflectance, transmittance, or absorptance are all functionally linked over the optical domain through the leaf absorption coefficient  $K$  that depends on leaf biochemical composition and wavelength through the specific absorption coefficient of each constituent (Baret and Jacquemoud, 1993). As a consequence, for a given leaf structure, leaf optical properties could be represented either by reflectance, transmittance, absorptance, or absorption coefficient  $K$ . In the following we will relate leaf optical properties  $O_l$  to leaf reflectance  $\rho_l$ , thereby implicitly taking into account the effect of leaf transmittance through the absorption coefficient  $K$ . This choice is made for practical reasons: In our experiments, leaf reflectance spectra are available, which is not the case for transmittance nor for absorptance or the absorption coefficient.

Canopy reflectance ( $\rho_c$ ) then becomes a function of several variables which all depend on wavelength except for the canopy structural variables ( $S$ ) because the size of canopy elements relative to the wavelength in the optical domain are different at least by an order of magnitude:

$$\rho_c = \rho_c(S, \Theta(\lambda), \rho_s(\lambda), \rho_l(\lambda), O_b(\lambda)) \quad (2)$$

The variable  $\Theta$  represents the view and source configuration and includes the fraction of diffuse incoming radiation which varies with the wavelength. As a first step, the spectral analogy comes directly from formula-

tion (2): When the optical properties of leaves and other vegetation elements, the soil reflectance, and the fraction of diffuse incoming radiation are all the same for two wavelengths  $\lambda_1$  and  $\lambda_2$ , then the canopy reflectances are also equal at those two wavelengths:

$$\left. \begin{aligned} \Theta(\lambda_1) &= \Theta(\lambda_2) \\ \rho_s(\lambda_1) &= \rho_s(\lambda_2) \\ \rho_l(\lambda_1) &= \rho_l(\lambda_2) \\ O_b(\lambda_1) &= O_b(\lambda_2) \end{aligned} \right\} \Rightarrow \rho_c(\lambda_1) = \rho_c(\lambda_2). \quad (3)$$

As a direct consequence, if the fraction of diffuse incoming radiation, soil background, and other vegetation elements can be considered either as spectrally flat or with very little effect on canopy reflectance, then a single relationship is observed between canopy and leaf reflectance over the whole optical domain. This relationship will be used later to reconstruct canopy reflectance spectra over the whole spectral domain from knowledge acquired over a selection of the spectral domain.

### Canopy Reflectance Sensitivity to Leaf Reflectance

*Theoretical Considerations.* The first derivative of canopy reflectance as a function of wavelength is given by

$$\frac{\partial \rho_c}{\partial \lambda} = \frac{\partial \rho_c}{\partial \Theta} \frac{d\Theta}{d\lambda} + \frac{\partial \rho_c}{\partial \rho_s} \frac{d\rho_s}{d\lambda} + \frac{\partial \rho_c}{\partial \rho_l} \frac{d\rho_l}{d\lambda} + \frac{\partial \rho_c}{\partial O_b} \frac{dO_b}{d\lambda}. \quad (4)$$

Canopy reflectance sensitivity to leaf reflectance  $\partial \rho_c / \partial \rho_l$  is then evaluated from Eq. (4):

$$\frac{\partial \rho_c}{\partial \rho_l} = \left( \frac{d\rho_l}{d\lambda} \right)^{-1} \left( \frac{\partial \rho_c}{\partial \lambda} - \frac{\partial \rho_c}{\partial \Theta} \frac{d\Theta}{d\lambda} - \frac{\partial \rho_c}{\partial \rho_s} \frac{d\rho_s}{d\lambda} - \frac{\partial \rho_c}{\partial O_b} \frac{dO_b}{d\lambda} \right). \quad (5)$$

In many practical cases, when ground targets are observable from space sensors, the diffuse fraction of incoming light is low. In these conditions, Clevers and Verhoef (1993) showed that canopy reflectance is not very sensitive to variations of this variable ( $\partial \rho_c / \partial \Theta \approx 0$ ). Furthermore, outside the blue spectral region, the fraction of diffuse incoming light varies only slightly with the wavelength ( $d\Theta / d\lambda \approx 0$ ). When the contribution of the bark or the soil background is negligible, as in the case of very dense canopies, very dark soil or bark ( $\partial \rho_c / \partial \rho_s \approx 0$  or  $\partial \rho_c / \partial O_b \approx 0$ ) or when the bark and soil optical properties are considered spectrally flat in a given spectral domain ( $d\rho_s / d\lambda \approx 0$  or  $dO_b / d\lambda \approx 0$ ), Eq. (5) reverts to the very simple form:

$$\frac{\partial \rho_c}{\partial \rho_l} = \frac{\partial \rho_c}{\partial \lambda} \left( \frac{d\rho_l}{d\lambda} \right)^{-1}. \quad (6)$$

Canopy reflectance sensitivity to leaf optical properties may therefore be evaluated through the spectral variation observed concurrently at canopy and leaf levels.

*Model Simulation.* Modeling canopy reflectance provides a convenient way to investigate canopy reflectance sensitivity to leaf optical properties. In the following,

we will use Eq. (6) to analyze the sensitivity of canopy reflectance to leaf reflectance from model simulations.

The PROSPECT model (Jacquemoud and Baret, 1990) was used to compute leaf reflectance and transmittance as a function of an absorption coefficient  $K$  and a parameter  $N$  representing the leaf mesophyll structure. For simplicity, the refraction index of leaf material was assigned to a fixed average value ( $n = 1.40$ ) assumed independent of wavelength. Previous analysis (Jacquemoud and Baret, 1990) showed that a small variation of this refraction index only slightly affects leaf optical properties. For our purpose, we simulated a range of leaf optical properties by varying the leaf absorption coefficient in a wide range ( $0.00001 < K < 5$ ) that covers the usual values encountered in the optical domain. The leaf mesophyll structure index was kept to an average value of  $N = 1.5$ . The SAIL model (Verhoef, 1984; 1985) is then used to compute canopy bidirectional reflectance. We assumed that the soil reflectance was spectrally flat and lambertian. We performed the simulations for a simple configuration: nadir viewing, with a  $45^\circ$  sun zenith angle, assuming that all the incoming radiation originates from the sun direction (no diffuse incoming radiation). We first simulated a "standard" case that corresponds to a quasi spherical leaf inclination (average leaf inclination:  $\theta_l = 60^\circ$ ), a soil reflectance of 0.15, and a range of leaf area indices ( $l = 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8$ ). We then changed the average leaf angle inclination ( $\theta_l$ ) and soil background reflectance  $\rho_s$ . Canopy reflectance sensitivity to leaf optical properties was evaluated using a variation of Eq. (6):

$$\frac{\partial \rho_c}{\partial \rho_l} = \frac{\partial \rho_c}{\partial K} \left( \frac{d\rho_l}{dK} \right)^{-1}. \quad (7)$$

The derivatives  $\partial \rho_c / \partial K$  and  $\partial \rho_l / \partial K$  were evaluated numerically.

We will discuss successively the effects induced by variations in leaf area index, soil reflectance, and leaf inclination (Fig. 1).

- *Leaf area index.* Figure 1a shows that canopy reflectance sensitivity to leaf reflectance obviously increases when leaf reflectance increases. For low leaf area indices, the sensitivity is very small and does not change very much with leaf reflectance. Conversely, for dense canopies, canopy reflectance is very sensitive to changes in leaf reflectance, particularly for highly reflecting (and transmitting) leaves. This behavior is mostly explained by the enhancement of the leaf signal through the multiple scattering process.
- *Soil reflectance.* The sensitivity of canopy reflectance to leaf reflectance depends on soil op-

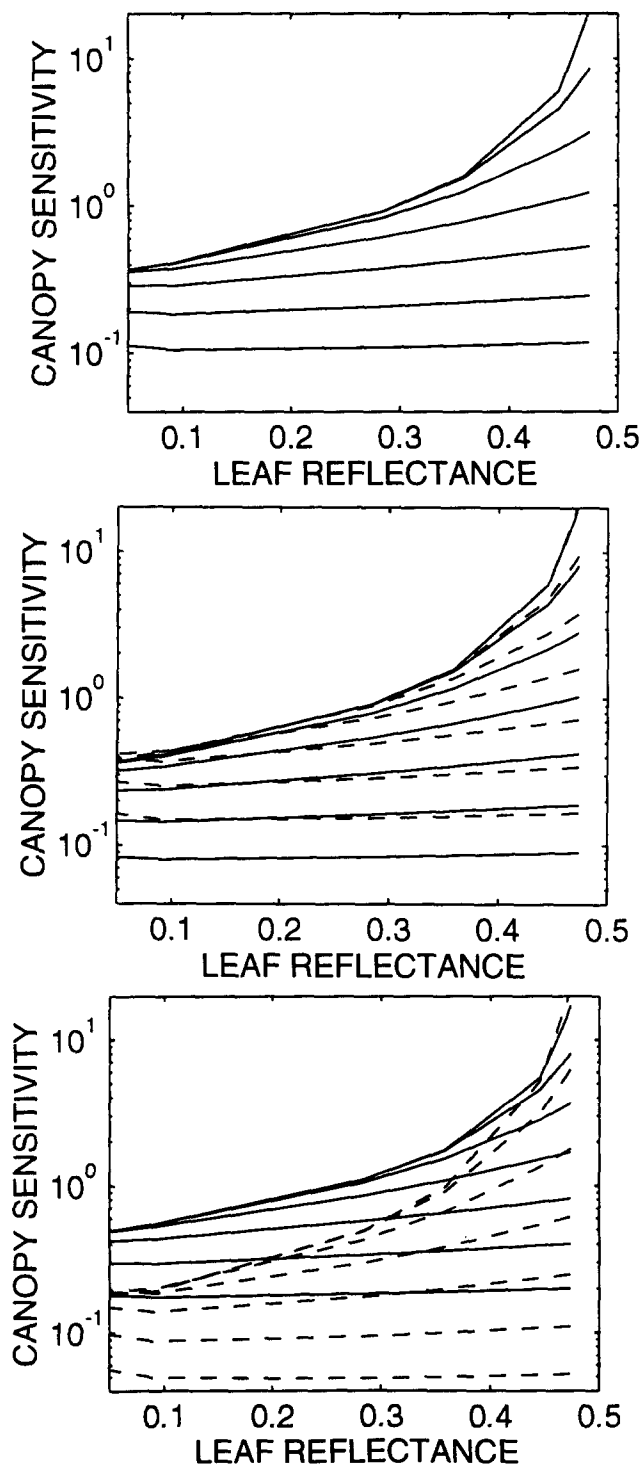


Figure 1. Sensitivity of canopy reflectance to leaf reflectance  $\partial\rho_c / \partial\rho_l$ . Results from model simulation for nadir viewing,  $45^\circ$  sun zenith angle, and no incoming diffuse radiation. Soil reflectance is assumed spectrally flat and lambertian. Graph a) corresponds to the standard case characterized by a leaf mesophyll structure index  $N=1.5$ , soil reflectance  $\rho_s=0.15$ , a range of leaf area indices ( $l=0.2, 0.4, 0.8, 1.6, 3.2, 6.4, \text{ and } 12.8$ ), and a quasispherical leaf inclination distribution ( $\theta_l=60^\circ$ ). Other graphs: Graph b) presents variations around this standard case due to soil reflectance  $\rho_s=0.05$  (solid lines) and  $\rho_s=0.30$  (dotted lines);

tical properties (Fig. 1b). An increase of soil reflectance increases canopy sensitivity to leaf optical properties significantly for low vegetation cover. This effect is attributed to the enhancement of the reflected signal by multiple scattering. For high leaf area indices, there is almost no effect of the soil background, as expected.

- *Leaf inclination.* For a given leaf area index, planophile canopies ( $\theta_l=20^\circ$ ) are more sensitive to leaf absorptance changes than erectophile canopies ( $\theta_l=80^\circ$ ) (Fig. 1c). This is explained by the increase of vegetation cover fraction and hence of multiple scattering observed for the more planophile canopies.

This brief sensitivity analysis shows that, for low vegetation cover, 1% increase of leaf reflectance results in about 0.1–0.5% increase of canopy reflectance. For dense canopies with full cover, and for high values of leaf reflectance, 1% leaf reflectance variation induces about 0.5–10% canopy reflectance variation.

In the next section we illustrate these theoretical results using data from a field experiment, in which canopy and leaf reflectance were measured concurrently.

## APPLICATION TO SUGAR BEET CANOPIES

### The Experiment

The experiment took place in Grignon ( $48^\circ51'N-1^\circ58'E$ ) in July 1990. The experiment is described in detail in Malthus (1990).

A range of sugar beet canopy structures was obtained by varying plant density. For each of the plots, leaf area index was estimated as the product of the average leaf area per plant measured over five plants times the actual plant density. To obtain a spectrally flat and dark background, we covered the soil with a black fabric ("SOLAR," Edmund Bell and Co., Bradford, U.K.). The reflectance of this fabric ranges from 0.03 in the visible to 0.10 at 2500 nm, with a very flat spectrum (Fig. 2). Unfortunately, for the highest leaf area index structure ( $l=2.85$ ), the only background available was the natural soil which was not spectrally flat.

Nadir canopy reflectance measurements were performed using the GER MK IV IRIS spectroradiometer fixed on a trolley at 4.75 m height, with a  $3^\circ \times 6.5^\circ$  field of view. Measurements were collected under clear sky conditions (diffuse fraction around 13% in the 500–590

graph c) presents variations around this standard case with leaf inclination  $\theta_l=20^\circ$  (solid lines),  $\theta_l=80^\circ$  (dotted lines). For each graph, the highest curve corresponds to the highest leaf area index.

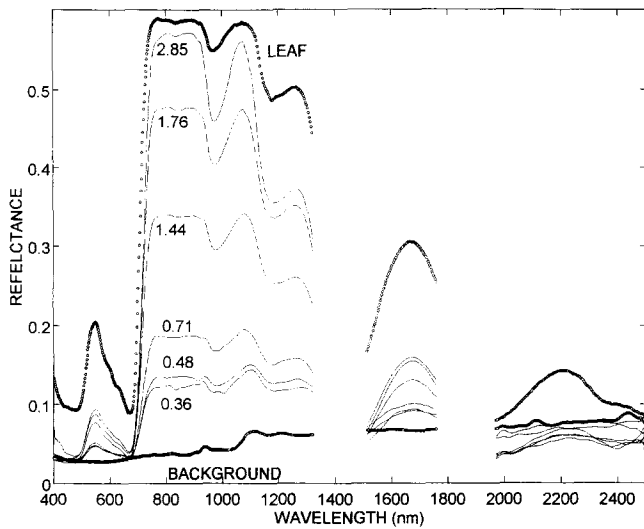


Figure 2. Canopies (solid line), leaf reflectance and black cloth (dotted) measured spectra. Each canopy is characterized by its leaf area index. All the spectra were smoothed using a 12 nm window.

nm domain), with a solar zenith angle close to  $40^\circ$ . Radiance from the target and from a white panel were recorded simultaneously in 975 channels ranging between 400 nm and 2500 nm with a spectral resolution of 2 nm, 4 nm, and 5 nm, respectively, for the 400–1000 nm, 1000–1800 nm, and 1800–2500 nm domains. The target signal was ratioed by the white panel signal. Absolute bidirectional reflectance was then computed by comparison with measurements over a primary reference panel. The absolute directional and spectral properties of this primary reference panel were previously characterized in the laboratory (Malthus, 1990). Spectral calibration was checked using well known atmospheric absorption features such as water and oxygen. For each plot, the average of four spatial replicates was computed.

Reflectance of leaf upper face was measured in the laboratory with the same spectroradiometer. The leaves were illuminated with a 1000 W halogen lamp placed at a 0.5 m distance from the target and at  $30^\circ$  zenith angle incidence. Nadir reflectance was recorded with the spectroradiometer with the same field of view and placed at 0.5 m height. The data were calibrated by comparison to a reference panel for which the spectral and directional properties were known accurately. The leaves were placed over the black fabric to minimize the contribution of the background. The average of 10 individual spectra was used. Figure 2 shows the resulting spectra.

To minimize problems induced by experimental noise, we smoothed both canopy and leaf spectra with a 12 nm window. Further, canopy reflectance data in the atmospheric water absorption bands (1322–1526

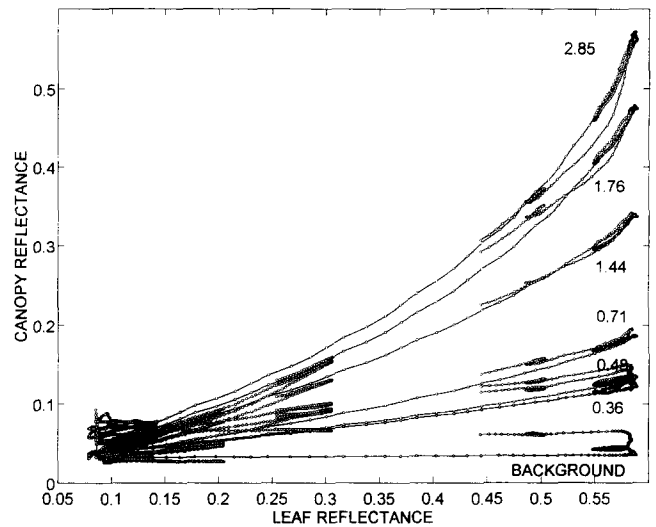


Figure 3. Relationship between canopy and leaf reflectance. Dots correspond to experimental data points. Six sugar beet canopies with leaf area index ranging 2.85, 1.71, 1.44, 0.48, and 0.36 are presented along with the relationship for the background material. This relationship is derived from concurrent measurements of leaf and canopy reflectance over the whole spectral domain (400–2500 nm except the water absorption bands).

nm and 1759–1970 nm) were not presented because of insignificant signal.

### Spectral Analogy over the Whole Optical Domain

For the sugar beet canopies that were sampled over the black fabric background, the following conditions were approximately met: The diffuse fraction of incoming radiation was very small, the soil background was dark and spectrally flat, and no other vegetation elements except leaves were present. For the largest leaf area index value, the spectrally variable soil reflectance was counterbalanced by its small effect on canopy reflectance. Therefore, a single relationship between canopy reflectance and leaf reflectance would be expected over the whole optical domain, according to the theoretical considerations on spectral analogies discussed earlier. Figure 3 shows the experimental relationships established over the 400–2500 nm (except atmospheric water absorption bands) spectral domain between canopy reflectance and leaf reflectance. Canopy reflectance increases as leaf reflectance increases. This behavior is more pronounced for well-developed canopies. The entire range of variation can be obtained in the red edge domain (from 681 nm to 744 nm) where leaf reflectance increases from a minimum value of about 0.08 to a maximum value around 0.58. In the near-infrared plateau (from 744 nm to 1300 nm) characterized by high leaf reflectance values, the relationship is slightly different from the one observed in the red edge

(Fig. 3). This is particularly obvious for low vegetation densities, where the “hysteresis” pattern can be easily attributed to the slight spectral variations of the black fabric that served as background. In the visible and in the middle infrared where leaf reflectance is small, the situation seemed more complex, with a significant scattering around an average trend depicted in the red edge. A large part of the scattering could be also attributed to the background spectral properties.

To test the applicability of the spectral analogy concept for spectrum reconstruction, we first extracted the relationships between canopy and leaf reflectances in the red edge domain (681–744 nm) for each of the seven canopy structures including bare soil corresponding mainly to a variation in leaf area index. Then, we used this relationship to compute canopy reflectance spectra from leaf reflectance spectra measured over the whole spectral domain. To estimate canopy reflectance from leaf reflectance, simple linear interpolation between the two nearest leaf/canopy reflectance values observed in the red edge was used. The approach is schematized in Figure 4. Results show a good agreement between actual canopy spectra and spectra simulated from leaf reflectance spectra and the canopy/leaf reflectance relationships observed over the red edge ( $R^2 = 0.92$ ,  $RMSE = 0.015$ ,  $n = 5369$ ). Figure 5 shows that, for low leaf area indices, the residuals exhibit the same pattern as soil background spectra. The extreme case is demonstrated when the technique is applied to the bare background: The residual is obviously almost identical to the measured soil background spectra. This shows the limits of this technique when applied to low vegetation covers and when the soil background is not spectrally flat. For medium leaf area indices, the background features almost disappear, and the maximum

Figure 4. Flow chart presenting the approach used to compute canopy reflectance spectra over the whole spectral domain from leaf reflectance spectra over the same domain and the relationship between canopy and leaf reflectances observed over the red edge domain.

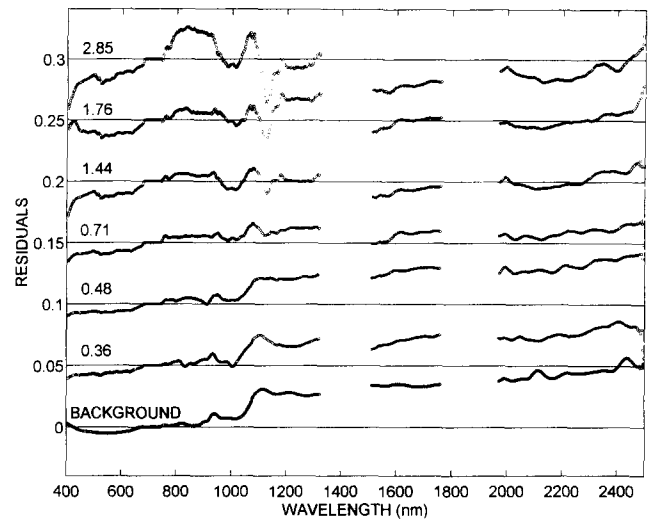
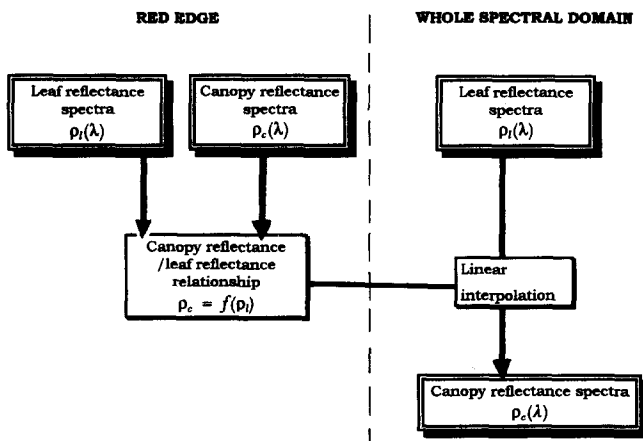


Figure 5. Residuals  $\Delta = \rho_c(\lambda) - \beta_c(\lambda)$  between simulated  $[\hat{\rho}_c(\lambda)]$  and measured  $[\rho_c(\lambda)]$  canopy reflectance spectra. The simulated spectra were derived as indicated in Figure 4. Each curve corresponds to a particular canopy. Each successive canopy is offset by 0.05 to improve readability.

difference between simulated and measured canopy reflectance is less than 0.02. For higher leaf area indices, some discrepancy appeared in the 800–1200 nm domain in relation to water absorption bands. This could be partly due to instrumental artifacts such as a slight wavelength calibration difference between leaf and canopy measurements. However, the deviation observed for the highest leaf area index could also be due to the background that was the natural soil and had a higher reflectance value in the 800–1300 nm domain as compared to the red edge. Nevertheless, the maximum residual value is still lower than 0.03.

### Canopy Reflectance Sensitivity to Leaf Reflectance

As demonstrated by Eq. (6), canopy reflectance sensitivity to leaf reflectance can be investigated by computing the first derivatives of canopy and leaf reflectance spectra. To minimize numerical problems when computing the ratio of small derivatives such as in the near infrared plateau, we focus on the red edge (681–744 nm) where the first derivatives of both canopy and leaf spectra are large. Figure 6 shows a good agreement with results obtained previously from the model simulations. For low leaf area indices, the sensitivity is below 0.5 and does not increase with leaf reflectance. Conversely, for higher leaf area indices that correspond to almost full cover,  $\partial\rho_c/\partial\rho_l$  can be greater than 1.0 for leaf reflectances higher than 0.4. We fitted the relationship between  $\partial\rho_c/\partial\rho_l$  and  $\rho_l$  canopy reflectance sensitivity to leaf reflectance to the following empirical equation:

$$\frac{\partial\rho_c}{\partial\rho_l} = a(l)\rho_l^l + b(l), \quad (8)$$

where  $a(l)$  and  $b(l)$  are parameters that depend on can-

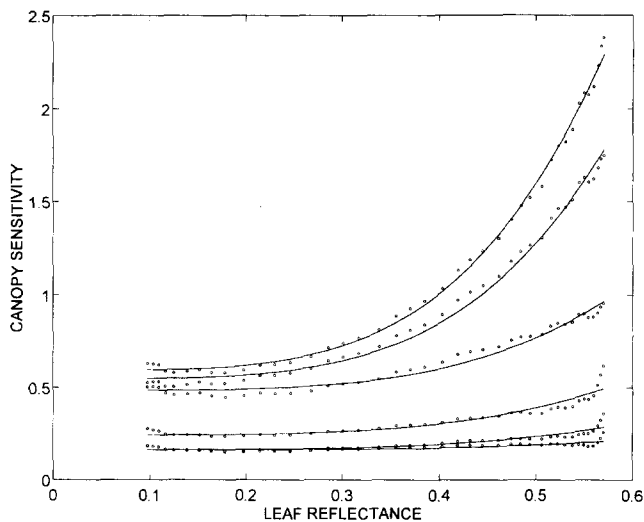


Figure 6. Canopy reflectance sensitivity to leaf reflectance ( $\partial\rho_c/\partial\rho_l$ ) as a function of leaf reflectance. Dots correspond to measured values over the red edge (681–744 nm). Solid lines correspond to the fitting to Eq. (7). Six sugar beet canopies with leaf area index ranging from 2.85, 1.71, 1.44, 0.48, and 0.36 are shown. The upper curve corresponds to the highest leaf area index (2.85). The lowest curve corresponds to the smallest leaf area index (0.36).

opy structure (such as leaf area index  $l$ ) and  $n$  is a parameter that appeared to be not dependent on canopy structure ( $n = 4.0$ ). Figure 6 shows the good match between the fitted and experimental points.

## CONCLUSION

The spectral analogy presented in this article is based on the assumption that the intrinsic scattering properties of the leaves represented by the real refractive index of leaf materials depend very little on wavelength. This could be formally investigated at the leaf level by analyzing the scatter around the relationship between leaf reflectance and transmittance for a given leaf. However, the low scatter observed around the relationship between canopy and leaf reflectance for each canopy structure indirectly demonstrates the validity of this assumption for our experimental conditions. The generality of this assumption should be investigated over a wide range of conditions to check its domain of validity.

This result has important implications for model simulation purposes. If the canopy/soil background composite reflectance signal is to be deconvolved, then spectral variations in reflectance originating from the pure canopy component can be simulated in two steps as illustrated in this article (Fig. 4): i) development of the relationship between canopy reflectance and leaf reflectance over the full range of leaf reflectance values and ii) computation of canopy spectral variation using leaf reflectance spectra and the previously developed canopy/leaf relationship. This process could save a lot

of time since the relationship between canopy reflectance and leaf reflectance is quite simple and very smooth, requiring very few points to be drawn. It could be very important if computationally intensive but asymptotically exact techniques such as ray tracing are to be used. However, this process requires computation of a pure vegetation signal and then its interaction with a given soil background in order to simulate the actual spectral variation of canopy reflectance. The approach developed here could be adapted to address the sensitivity of canopy reflectance to soil background spectral reflectance variations.

One of the main issues that could drive the development and the specifications of the next generation of imaging spectrometers is the demonstration of the capacity of high spectral resolution sensors to provide explicit information about canopy biochemistry. The question that remains unsolved is: Is the weak biochemical signal observed at leaf level still detectable at canopy level? We show that the problem could be split into two parts: investigation of the sensitivity of leaf optical properties to leaf biochemical composition and evaluation of canopy reflectance sensitivity to leaf reflectance. We have used the canopy spectral analogy to investigate canopy reflectance sensitivity to leaf reflectance. The experimental results show good agreement with model simulations. Both results demonstrate that the leaf biochemical signal could be enhanced at the canopy level by a factor that can be greater than 2.0. Multiple scattering was recognized as the primary physical process that drives this signal enhancement. However, to get a canopy reflectance sensitivity to leaf reflectance greater than 1, the vegetation should be dense with a full vegetation cover, and measurements should be performed in spectral domains where reflectance is high (greater than 0.40 in our conditions). The near-infrared plateau (800–1300 nm) seems the most promising spectral region. The main absorption features in this spectral region correspond to the first overtones of water O–H absorption at 970 nm and 1200 nm (Curran, 1989) that may mask the similar O–H starch, cellulose, or lignin absorption features. Nevertheless, weak secondary and tertiary overtones of C–H and N–H exist around 1030 nm that could possibly be used for protein or oil content estimation, if detectable.

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