Validation of a leaf reflectance and transmittance model for three agricultural crop species

Application Note

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Abstract

Reflectance and transmittance have been measured for a selection of leaves from three cereal crop species using a laboratory based Cary 500 spectrophotometer. Spectral measurements, along with ancillary data describing chlorophyll, water and dry matter content per unit leaf area, have been used to assess the accuracy of the Prospect model [1] for estimating leaf reflectance and transmittance. An inversion technique has also been applied to the model to derive leaf pigment and leaf water content. This has produced acceptable estimates of the true variation in these parameters. This result indicates that the Prospect model, in conjunction with a suitable method to account for canopy architecture and soil reflectance, has potential to contribute to the generation of crop status information products based on hyperspectral data.

Introduction

Increasingly, surface reflectance estimates derived from hyperspectral data are used to assess spatial variance in crop condition and biomass over large agricultural fields. The distribution and optical properties of individual plant leaves are the primary factors contributing to the reflectance of a mature crop canopy. Consequently, to develop valuable information products from these data sources, an understanding of the reflectance and transmittance of individual plant leaves is essential.

The Prospect leaf reflectance and transmittance model [1] has been developed using contemporary theories of radiative transfer within leaf material. However, the inherent variability in biochemical constituents and leaf structure among plant species requires that accurate laboratory validation of the model be undertaken before it can be used reliably for agricultural crop condition assessment.

In this experiment, three cereal crop species (barley, oats and wheat) were chosen for analysis. Plants were sown in pots and placed in a greenhouse for four weeks prior to measurement. Etiolates were produced by placing selected plants in complete darkness over the final two weeks to inhibit chlorophyll synthesis. To examine the effect of variations in leaf water content, a selection of wheat leaves were picked 24 hours, 12 hours and 2 hours prior to measurement and placed in a warm oven set at 60 °C.

Healthy and etiolated leaves were picked from each plant an hour prior to spectrophotometric measurement. Replicates of each sample were selected and prepared for destructive analysis to derive values for the Prospect model input parameters; chlorophyll a and b, leaf water and leaf dry matter content per unit area of leaf matter.

Spectral measurements

The reflectance and transmittance of leaf samples were recorded over wavelengths from 350 nm to 2500 nm using a laboratory based Cary 500 spectrophotometer. The instrument was fitted with a 110 mm diameter integrating sphere, permitting the sum of direct and diffuse radiation to be the measured. A total of 28 spectra were recorded, constituting 14 pairs of reflectance and transmittance measurements.

Comparison between healthy and etiolated wheat leaf spectra shows the distinct impact on reflectance and transmittance due to pigment content. As shown in Figure 1, reflectance in the visible red region is reduced considerably in the etiolated leaves due to the inhibition of chlorophyll synthesis. The etiolated leaf spectra still exhibit a significant drop in response in the visible blue region due to the carotenoid group of pigments, which develop in leaves even in the absence of light [2].

The reflectance of a healthy wheat leaf also illustrates the major water absorption bands centered at 1450 and 1940 nm, easily distinguishable in fresh leaf spectra. However, the weaker liquid water absorption bands documented by [3] and centered at 760, 970, 1190, are more difficult to distinguish. The reflectance of a dry wheat leaf in Figure 1 shows a dramatic reduction in the near infrared. Remnant absorption featured across this region is due to biochemicals such as protein and cellulose. Chlorophyll absorption in these dry leaves remains strong due to the rapid nature of the drying process.

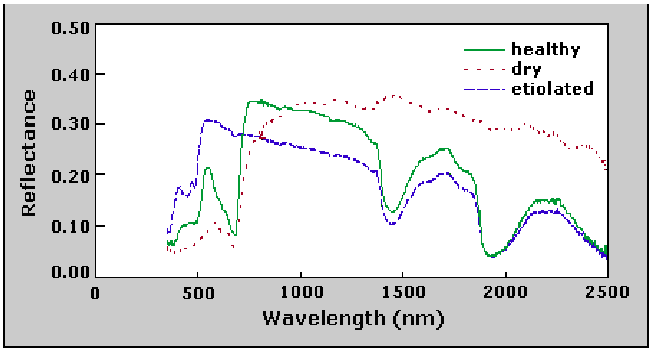

Figure 1. Reflectance spectra of healthy, dry and etiolated wheat leaves measured using the Cary 500 spectrophotometer

Variations in leaf thickness were simulated by stacking multiple leaves over the integrating sphere port. Leaf thickness contributes to the relative proportion of reflected versus transmitted light in each wavelength, altering the number of refractive index changes encountered in a direct path through the leaf, while also increasing the quantity of absorbing material present. This ratio of reflected versus transmitted light is highlighted in Figure 2, where the stacking of multiple leaves has increased the reflectance and decreased the transmittance, particularly in the low absorbing near infrared region.

Ancillary data

Three sets of absorption coefficients [1, 4, 5] have been defined for the Prospect model since its inception. Those used by [5] were selected for this study, as it was more practical to measure dry matter content than the specific biochemicals used by [4]. As a result, the model parameters used to compute leaf reflectance and transmittance comprised the content of chlorophyll, water and dry matter per unit leaf area, as well as a leaf structure parameter, to help define the amount of reflectance versus transmittance.

In order to determine chlorophyll content per unit leaf area, images of each leaf were recorded using a flat bed scanner and leaf area computed using digital image analysis. Each leaf was then ground in acetone to extract the leaf pigments and the solution filtered to remove undissolved leaf matter. Absorption of the dissolved pigment solution was measured using a spectrophotometer and normalized for solvent volume and leaf area. The content of chlorophyll $a + b$ in the leaves was computed according to the method of [6] and recorded in units of $\mu g/cm^2$ of leaf area.

To derive leaf water and dry matter content, leaf area was again determined using digital image analysis. The fresh leaves were weighed and then placed in a warm oven set at 60 °C, for three days. When removed, a dry weight was recorded and this considered the true weight of dry matter in the fresh leaf. The difference between fresh and dry weights was assumed to account for the weight of water in the fresh leaf. Each weight was normalized for the respective leaf area and recorded in units of g/cm^2.

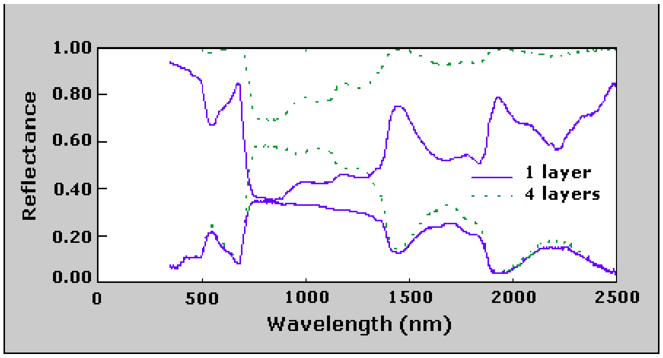

Figure 2. Reflectance (lower curves) and 1-transmittance (upper curves) measured for a single barley leaf layer (solid lines) and for a stack of four barley leaves (dotted lines)

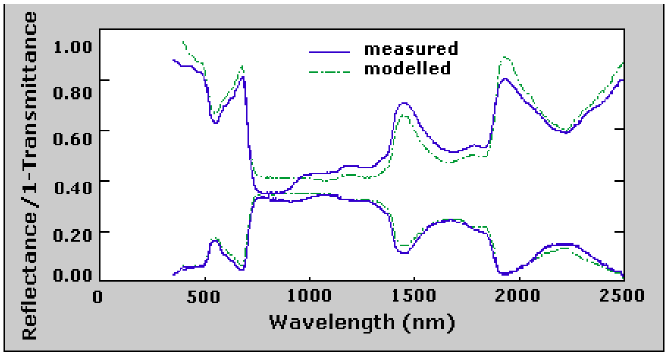

Figure 3. Graphical presentation of measured reflectance and 1-transmittance spectra (solid lines) and those produced using the Prospect model (dashed lines)

Model validation

Figure 3 shows a strong relationship between measured cereal crop leaf reflectance and transmittance spectra to those computed using the Prospect model. Correlation in the visible red chlorophyll absorbing region and the two major water absorption bands in the near infrared are particularly promising for inversion of the model.

Within the theoretical framework of the Prospect model, the leaf is considered to be a series of flat homogeneous plates. The relative proportion of light reflected and transmitted is accounted for by the structure parameter indicating the number of plates in the leaf structure, and the refractive index of these plates. The lowest value accepted by the model for this structure parameter is one. This was the value used for the computation of all spectra, except where multiple leaves were stacked over the integrating sphere port.

One apparent inconsistency between measured and modelled spectra is the general overestimation of reflectance and underestimation of transmittance. This is obvious in Figure 4, which shows the average modelling error for all measured and modelled spectra. This overestimation would be best addressed by reviewing the refractive index used for model calculations. It is assumed that lower refractive index values would allow a more meaningful structure parameter to be set and produce more accurate spectra.

One feature of the measured cereal crop leaf spectra that is not accounted for in the model is the dissimilarity between reflectance and transmittance spectra in the low absorption regions of the near infrared. A substantial increase in the transmittance centered in the region of 800 nm was seen in all fresh leaf spectra. However a corresponding increase is not displayed in the reflectance curves. This causes the underestimation of transmittance in this region seen in Figure 4. A possible reason for this feature is some form of anisotropic scattering causing a dominance of forward scattering. There is no easy way to account for wavelength dependent scattering features in the Prospect model other than to adjust the refractive index in this region. This is another motivation for investigating a possible underestimation of the refractive index in future work.

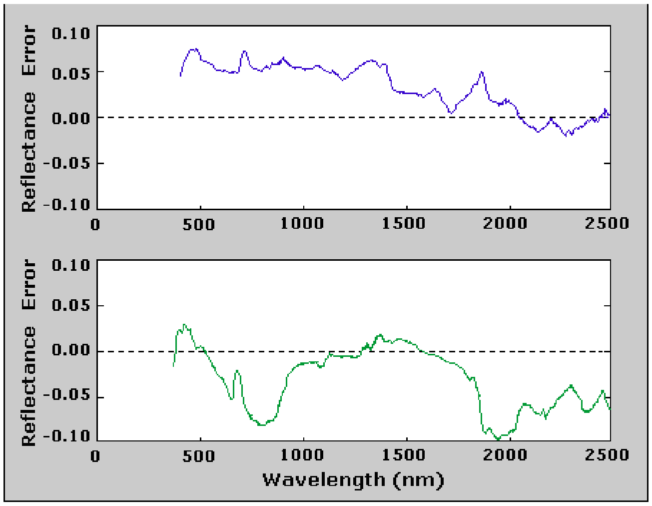

Figure 4. Average modelling error (modelled-measured) for the 14 reflectance and transmittance spectra

Model Inversion

The merit function shown below, defined by [1], was applied to the data to find a set of model parameters that minimize the difference between measured and modeled spectra. In this equation Δ^2 is the function to be minimized, $R_{Cary500}(\lambda)$ and $T_{Cary500}(\lambda)$ and the reflectance and transmittance at wavelength λ measured using the Cary 500, and $R_{Model}(\lambda)$ and $T_{Model}(\lambda)$ are the corresponding reflectance and transmittance estimated using the Prospect model.

$$\Delta^2 = \sum_{\lambda=400}^{2500}\left[\left(R_{Cary500}(\lambda)-R_{Model}(\lambda)\right)^2+\left(T_{Cary500}(\lambda)-T_{Model}(\lambda)\right)^2\right]$$

A generalized reduced gradient (GRG) constrained minimization routine [7] was used to minimise the merit function and derive estimates of leaf structure, leaf pigment, water and dry matter content. The values for chlorophyll and water were compared to measured values (Figure 5). Retrieval of leaf water content per unit leaf area was encouraging with only a slight overestimation shown by the best fit linear coefficient of 1.09824 and an R^2 of 0.9289. Chlorophyll content had a greater tendency for overestimation with a linear coefficient of 1.2399 and a reduced precision with an R^2 of 0.7846. Values retrieved from the inversion process versus their measured value are plotted in Figure 5.

Conclusions

The results of this work have shown that problems exist in the estimation of cereal crop leaf reflectance and transmittance using the Prospect model. This leads to inaccuracies in the retrieval of chlorophyll and leaf water content through model inversion. However, further work to adjust the leaf refractive index may help to address these problems and to achieve better estimates of these parameters.

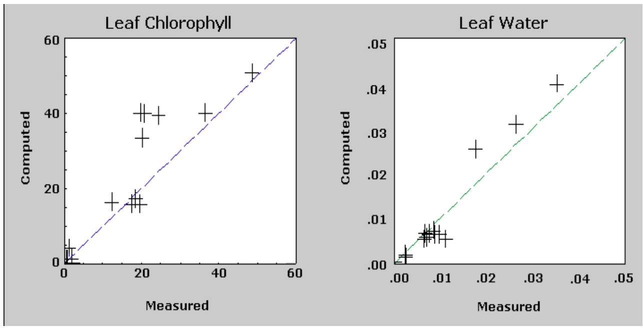

Figure 5. Values retrieved for leaf chlorophyll content and leaf water content plotted against their measured values, along with the line showing the ideal 1 to 1 relationship

With further work to identify its shortcomings specific to cereal crop analysis, the Prospect model, when coupled with a suitable canopy reflectance model, may prove a valuable tool in the monitoring and management of agricultural crops using hyperspectral data.

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